ALLOYS OF IRON RESEARCH, MONOGRAPH SERIES

FRANK T. SISCO, Editor

THE ALLOYS OF IRON AND NICKEL

Vol. I—SPECIAL-PURPOSE ALLOYS

ALLOYS OF IRON RESEARCH
Monograph Series

THE ALLOYS OF
IRON AND NICKEL

Vol. I—SPECIAL-PURPOSE ALLOYS

BY

J. S. MARSH

Physical Metallurgist and Associate Editor,
Alloys of Iron Research

First Edition

ALLOYS OF IRON RESEARCH
MONOGRAPH SERIES

THESE monographs are a concise but comprehensive critical summary of research on iron and its alloys as reported in the technical literature of the world. They contain a discussion of all available data on binary and higher ferrous alloy systems, and on the effect of the alloying elements on carbon steel and on simple and complex alloy steels and special alloy cast irons. They provide a reliable foundation for further research and supply to the practical metallurgist, steel worker, foundryman, and engineer the essential information now scattered through more than two thousand journals and text-books in many languages.

The authors are responsible for selection and evaluation of the data, for arrangement of subject matter, and for style of presentation. Each book, however, has been reviewed in manuscript by men especially qualified to criticize all statements. Indebtedness for this cooperation is recognized in the Acknowledgments. Finally, each manuscript has been reviewed and approved for publication by the Iron Alloys Committee.

The Committee expresses its appreciation to *The Engineering Foundation,* the *iron and steel, automotive and other industries of the United States and the American Iron and Steel Institute, Battelle Memorial Institute, The American Society for Metals, The American Foundrymen's Association,* and *National Bureau of Standards* for financial support, which made the laborious review of the world's literature possible; and to the libraries, engineering societies, and the technical press in the United States, Canada, England, Germany, France, Italy, Sweden, Japan, and Czechoslovakia, for cooperation in making available inaccessible reports and in permitting the use of published data.

PREFACE

Nickel is perhaps the most versatile of the elements commonly alloyed with iron. It is a component of many engineering steels and cast irons, of a series of alloys having coefficients of thermal expansion ranging from the negligible to the highest values found in ferrous metals, of alloys having the two extremes of magnetic permeability, of many alloys used because of their superior resistance to corrosion, and others. A detailed list of uses could be extended indefinitely, but one does not need this to become convinced that the iron-nickel system is of great importance to contemporary civilization. In keeping with that importance, its literature is vast and is by no means confined to purely metallurgical journals; technical and scientific articles including information on iron-nickel alloys number in the thousands. This made it impossible to compress the review into a single volume. This first volume—of two—is devoted to the constitution and properties of high-purity iron-nickel alloys and to the properties of special-purpose alloys. (The second will be concerned mostly with the engineering properties of nickel steels and cast irons.) The dividing line between the arbitrarily established fields of the two volumes is not very clear in some instances. Consequently there was considerable difficulty in apportioning some of the material; a few of the decisions undoubtedly will be questioned by some readers, but it is felt that the present disposition will result in the least confusion.

That there is ample material for two volumes is reflected by the fact that, even after elimination of the inevitable duplications and rehashes, a bibliography of over 600 items remained for this volume alone; consequently drastic condensation was necessary in several instances. An example is the chapters on magnetic properties, which could be expanded easily to book length. Decisions on what to include were guided by the aim of adequate coverage from the metallurgical point of view combined with sufficient comprehensiveness to be useful to the physicist and the electrical engineer. Here again it is probably impossible to

satisfy every reader; for example, much of the discussion is concerned with matters of interest at present only to the communication industries.   However, it is not impossible that some of the materials used in communication will be used in power transmission, because there is the possibility that their higher cost, as compared with present core materials, will be overcome by greater efficiency.   At the other extreme is the chapter on physical properties such as elastic constants and specific heat, which is much thinner than one would like it to be, owing to actual lack of reliable data which would be very useful in determining the interrelations among still other properties.   Such inequalities, however, seem to be inevitable.   Some of the gaps in knowledge will be closed by investigations in progress at the time of writing, but plenty will remain for future workers.   Spectacular discoveries have been made by investigators of the properties of iron-nickel alloys, and it seems likely that others will follow.

Finally, a word about units: In general they are the same as those used in previous monographs of this series, which is to say that the centigrade temperature scale is preferred, although the Fahrenheit equivalents are given as well wherever data are quoted that are likely to be of interest to engineers unaccustomed to thinking in terms of the centigrade scale.   Otherwise, the recommendations of such organizations as the American Society for Testing Materials and the American Standards Association have been followed as closely as possible.   This applies especially to discussions of mechanical and of magnetic properties.

<div align="right">J. S. Marsh.</div>

New York,
  October, 1938.

ACKNOWLEDGMENTS

CONTENTS

xi

THE ALLOYS OF IRON AND NICKEL

VOLUME I
SPECIAL-PURPOSE ALLOYS

CHAPTER I

INTRODUCTION

Historical—Meteoric Iron—Melting and Casting Iron-nickel Alloys—
Mechanical Treatment—Author's Summary

Iron-nickel alloys are of much historic interest; in the form of metallic meteorites they were probably the first ferrous materials used by man. There were not many of them but they were valuable, for they were malleable and tough and therefore much superior to stone tools and weapons. Industrial interest in manufactured alloys of iron and nickel is relatively recent, extending back about 50 years, with the extensive use of nickel as an alloy beginning about 20 years ago. The present value of nickel to ferrous metallurgy is evident from the amount used—for 1936 this was estimated to be 115 million lb.

Important consumers of iron-nickel alloys are the transportation industries—automotive, railway, aviation, and marine—and the communication industries—telephone, telegraph, and radio. The former have considerable interest in the saving of weight, and a good means of accomplishing this is to use stronger materials such as alloy steels and cast irons; increased corrosion resistance is a factor also. For the latter, a large measure of success depends upon the special properties of iron-nickel alloys. The list of uses to which ferrous alloys containing nickel can be put could be extended indefinitely, and time is sure to add still more; but it is sufficient to conclude that the iron-nickel system is one of the most important. Scientifically, it is less understood than some others, but it is comforting to note that many

1

of its "anomalous" behaviors are the very behaviors that are singularly useful in practical applications.

The enormous literature of iron-nickel alloys soon made it apparent that an adequate critical review would overflow a single volume.   It was, therefore, decided to restrict this volume, the first of two, to consideration of alloys that roughly may be termed "special purpose."   Although hardly perfect, this restriction facilitates a workable scheme.   Further, all information of the kind that might be called scientific is segregated in this volume.

The greater portion of the following pages is concerned with the constitution and physical properties of binary and more complex iron-nickel alloys; the smaller is devoted to mechanical properties and corrosion, mostly of low-carbon, high-nickel alloys.   Here the dividing line is difficult to draw.   It was finally decided that in the present volume attention should be paid to those iron-nickel alloys containing so much nickel (more than about 6 per cent) that, regardless of the carbon content, they are not commonly used as structural and engineering steels. In the case of the iron-nickel alloys modified by other elements, principally chromium, it was decided to restrict the data included in this volume to those materials containing more than 6 per cent nickel and more nickel than chromium.   There are a few exceptions to this arbitrary classification, but the reason for these exceptions will, it is believed, be clear in the places where the data appear.   The second volume of the monograph will give a summary of data on the manufacture and properties of the nickel and nickel-alloy steels commonly used for engineering and structural applications and containing generally less than about 6 per cent nickel.   It will be also a summary of information on all the nickel-containing cast irons.

It was further difficult to avoid all conflict with the data on iron-nickel-chromium alloys which appear in Volume II of "The Alloys of Iron and Chromium."*   Discussion of data on such materials as the 18 per cent chromium, 8 per cent nickel alloys clearly belongs in that volume.   The classification of other stainless and heat-resisting alloys is sometimes difficult; an effort has been made, however, to restrict the discussion in this book to those containing higher nickel than chromium except

* To be published soon.

where the inclusion of the higher chromium alloys permits an evaluation of the effect of nickel.

A. HISTORICAL

Nickel ores, their distribution, and reduction will be discussed in Volume II of this monograph. The earliest source of nickel, meteoric iron, can, however, be discussed with justification in this first volume. Although meteoric iron was used for the crude manufacture of tools and weapons at least 4000 years ago, it was not until late in the eighteenth century that nickel was found to be an important element in this material.

1. The History of Nickel.—Nickel was recognized as such relatively late in the history of metals. The name is derived from *Kupfernickel*, which could be translated "bedeviled copper." The traditional story is that medieval Saxon miners working in a silver mine came upon minerals that appeared to be good silver ore; upon smelting they yielded a great stench and no silver. The notion arose that the disagreeable material was a sort of supernatural copper ore, placed in that state by the nixes and kobolds. It is now known that the unwelcome minerals were arsenides of nickel and cobalt. Thus two common metals derive their names from dwellers of the nether regions, which is especially interesting in view of the fact that their very close relation, iron, was considered a gift from heaven in ancient times.

The idea that Kupfernickel—now known as niccolite—is a compound of copper persisted some hundreds of years, for it was not until 1751 that Cronstedt[1] announced the truth. However, in the form of alloys, nickel had been in use in some parts of the world for a long time. For example, analysis of Persian coins dating from the pre-Christian era has shown the presence of nickel (it is almost certain that this element was present in the ore used for making coinage metal). This is also true of the early Chinese alloy known as *pakfong* or *paktong*, which contains nickel, copper, and zinc.

2. Early History of Iron-nickel Alloys.—There is reliable evidence that the first iron used by man was of meteoric origin. Since all metallic meteorites consist principally of iron-nickel alloys, it is self-evident that the use of these alloys is older than that of any other ferrous material. The use of meteoric iron by primitive people has persisted down to relatively recent times;

in the eighteenth century explorers discovered isolated Eskimo tribes having various implements, such as arrow tips, spearheads, and knives, fashioned from meteoric iron. According to Zimmer[124] and to Rickard,[429] their method of making use of the material was about what would be expected of Stone Age people. The latter stated that:

. . . they detached pieces by laminating some slight prominence on the surface of the meteorite; they pounded repeatedly in the same place until a small ridge of metal was formed, and then they worried it apart, in the manner that the Indians used to separate the masses [of copper] they found in the Lake Superior region.

Subsequent discoveries, especially by archeologists in Egypt, indicated that meteoric iron was worked into jewelry thousands of years ago.

The history of man-made alloys of iron and nickel seems to date from 1754, because it was then that Cronstedt (according to Benedicks[208]) announced that "among the metals proper, iron has the greatest friendship for nickel." This statement was made as a result of an investigation of alloys of nickel and the known metals. Sixty-four years were then to pass before the world was presented with more information. In the meantime, the presence of nickel in meteoric iron was discovered. Stodart and Faraday,[2] as a result, attempted to prepare artificial meteoric iron by fusing horseshoe nails with 3 and 10 per cent nickel in an air furnace. Specimens of these alloys exist today and have been analyzed and tested by Hadfield.[380] They contain less than the intended amount of nickel, but there is no doubt that Stodart and Faraday made nickel steel. A few years later—in 1827—Berthier[3] in France found a meteorite from Mexico to consist essentially of iron and 8.6 per cent nickel. The strength and ductility of the metal were such that Berthier suggested the artificial preparation of such materials.

So far as is known, the first commercial application of iron-nickel alloys came shortly thereafter. In 1832, von Liebig[4] announced that a German steel maker had added nickel to iron and steel and found it possible "to develop the most beautiful damascene pattern." Suggested applications were locks and gun barrels. There is no evidence on the degree of success achieved, however. It seems unlikely that much was accom-

plished, for nickel must have been scarce, of low quality, and very expensive. Nickel as an alloying element received its first setback from Fairbairn[6] in 1858, who experimented with cast irons to which about 2.5 per cent nickel was added. He concluded that for the casting of heavy artillery, no material was better than the "best and purest cast iron." Fairbairn's nickel was obtained by reduction of roasted sulphide ore, consequently the product, according to current standards, must have been very impure, because the incomplete description of the process leads to the suspicion that both the oxidation of the sulphide and the reduction of the oxide were far from complete. Coincidently, Bessemer[19] had the idea of using nickel. The case is stated clearly by quotation from photographs of a memorandum book dated 1858:

> Meteoric iron guns, and other castings,—being an alloy of Nickel and pure or malleable iron, or steel, ? will Nickel render iron more easily · fusible and make it cast more sound.

Another page, dated 1862, contains:

> No. 3 pot.
> Iron shot—194 oz.,
> Nickel—6 oz.
> Cast clean ingot piped not sound, very soft, very strong, exceedingly tough cold, would not forge at steel heat but went all to pieces hammered cold, and was very soft and tough.

The experiment was not followed up and was not made public until 1895, upon discovery of the old notebook. Meanwhile, in the early 1870's, several patents were issued, in which claims were made for increased toughness and resistance to corrosion as a result of addition of nickel to iron and steel. Iron-nickel alloys were prepared in America as early as 1853, according to Colby,[47] but details are not known. Modern history of the alloys begins in 1885, for it was then that ferronickel was produced on a commercial scale in France, but it was not until four years later that the first systematic study of nickel steels appeared.

B. METEORIC IRON

Meteorites continue to be of interest because they furnish tangible evidence of the nature of extra-terrestrial matter. According to Merrill,[355] the most abundant meteoric elements are aluminum, calcium, carbon, iron, magnesium, nickel, oxygen, phosphorus, silicon, and sulphur. Chlorine, chromium, cobalt, copper, hydrogen, iridium, lithium, manganese, nitrogen, palladium, potassium, ruthenium, sodium, titanium, vanadium, and probably argon and helium are found in smaller quantities. Thus, qualitatively, the composition of meteorites and terrestrial rocks may be the same. In the forms of combination of elements, however, they often differ markedly. Furthermore, meteorites may be divided into stony and metallic classes.

3. Metallic Meteorites.—Metallic meteorites consist mostly of iron containing various percentages of nickel and cobalt. The early mineralogists recognized three constituents, which were named *kamacite, taenite,* and *plessite.* It is now known that *kamacite* is an alpha-phase alloy of essentially iron and nickel, that *taenite* is a gamma-phase alloy, and that *plessite* is merely a mixture of alpha and gamma phases (see page 50). Other constituents familiar to the metallurgist are the iron carbide containing nickel known as *cohenite* and iron-nickel phosphide known as *schreibersite.*

Many analyses show that there is no essential difference of composition between the metallic portions of stony meteorites and the all-metal meteorites. In addition, most meteorites of both kinds share characteristic external features. There is no known limit to the size of meteorites; however, the largest found weighed 37.5 tons and the smallest fall known consisted of a single stone weighing 5 g. According to Merrill, it is generally conceded that meteorites of any type or size are fragments when they enter the earth's atmosphere, and that further fragmentation and reduction of size take place during passage through the atmosphere. The final shape and size, therefore, depend upon the speed. In any event, sufficient heat is generated to fuse the surface, and such fusion plus stripping off of the molten material often gives rise to a fluted appearance. Since the metallic meteorites are tougher than the stony kind, they should have the greater resistance to fragmentation.

4. Structure of Metallic Meteorites.—The characteristic—Widmanstätten—structure of meteoric iron has been known for well over 100 years. Somewhat later, this structure was observed in terrestrial alloys, such as carbon steels. Then followed the attempt to produce it in artificial iron-nickel alloys, but without success at first. In brief, the structure is produced by the precipitation of a second solid phase from the parent phase. Its characteristic appearance results from the fact that the phases are crystallographically related (the precipitated *kamacite* plates are arranged with respect to one another as the faces of an octahedron).

The results of attempts to explain the structure of meteoric iron have been reviewed comprehensively by Mehl and Barrett.[392] They concluded that the first correct explanation of the origin of Widmanstätten figures was given by Osmond and Cartaud[58] in 1904. Otherwise their theory included a eutectoid transformation; in this they were followed by many others, and the notion seemingly persists among some writers on meteorites. It is shown in the next chapter that no eutectoid transformation occurs in iron-nickel alloys. A simple explanation of the origin of the structure of meteoric iron that is consistent with the facts was given recently by Derge and Kommel.[592] Part of the argument depends upon information given in Chapter II, but their general theory may be summarized here for the sake of unity. At temperatures somewhat less than temperature of freezing, iron-nickel alloys are in the gamma phase; such alloys at high temperatures tend to form large grains, which accounts for the large *taenite* grains required for subsequent formation of the Widmanstätten pattern. Upon further cooling of alloys of the nickel content of meteoric iron, the temperature is reached at which the alpha phase is precipitated—in meteorites as *kamacite* plates. Such transformation is accompanied by enrichment in nickel of the remaining gamma phase; finally, some of the gamma phase persists (*taenite*). *Taenite* of intermediate nickel content, corresponding to the range in which alpha and gamma phases coexist, undergoes partial transformation and gives rise to the constituent known as *plessite*. Impurities and rate of cooling undoubtedly have great effect on the final structure, but the explanation of Derge and Kommel is capable of accounting for all structures found in metallic meteorites.

C. MELTING AND CASTING IRON-NICKEL ALLOYS

Many of the problems connected with the melting and casting of the plain and modified iron-nickel alloys are those involved in the melting, refining, and the ingot and casting practice of the lower nickel alloy steels and the nickel cast irons, or the 18 per cent chromium, 8 per cent nickel stainless alloys. As noted previously in this chapter, the first class of materials, including their manufacture, will be discussed in Volume II of this monograph. The manufacture of the 18-8 alloys has been adequately covered in the second volume of "The Alloys of Iron and Chromium" and by Thum.[546] It only remains, therefore, to discuss in this present volume the details which are not covered in the volumes just mentioned.

5. Melting Iron-nickel Alloys.—As nickel does not oxidize preferentially to iron, there is no loss of nickel in melting these alloys. According to Callomon,[159] sound castings of a 36 per cent nickel alloy containing 0.5 per cent carbon, 0.5 per cent manganese, and 0.25 per cent silicon can be readily made by either the basic electric or the basic open-hearth process.

According to Potts,* because of the small tonnage produced and the different analyses required, a 6-ton basic electric furnace is ordinarily used with the same type of slag practice as is used for any high-grade electric-furnace steel. Although either rimmed or killed steel practice is practicable, the latter is preferred. High-nickel scrap in any amount may be used. Concerning the difficulties in melting Potts stated:

In the production of these alloys, much difficulty has been experienced due to their high dissolving power in the liquid state for certain gases, such as hydrogen, nitrogen, steam, hydrocarbons, alcohols, or combinations of these gases, which might be formed in an electric arc due to electrolytic or high temperature effects. These gases are not appreciably dissolved by deoxidizers and can only be removed from a molten bath by displacing them with some other gas (for instance, carbon monoxide which is in turn removable by deoxidizers), according to Dalton's law of partial pressures of gases in solution in a liquid. When melting by the electric arc process, it is impossible to prevent the bath from becom-

ing partially or completely saturated with these gases due to the action of the electrode arcs on bare metal during the melting down period. The amount of gas picked up by the bath increases as the melting voltage used increases. When melting down is complete, the bath should be covered with a slag (either lime-spar or lime-silica-sand type is satisfactory) after which it should be boiled by evolution of carbon monoxide for a period of 20 to 30 min. A boil that will produce bath waves about 1 to 2 in. high is sufficient.

After the boiling period, the slag should be deoxidized to a black carbide with carbon dust to make sure of low sulphur and a definitely known low oxygen content in the bath. After the slag has turned, alloy samples are analyzed for carbon, manganese, and nickel. If final composition adjustments are necessary, they are made and the bath is ready for final deoxidizers. If silicon alone is used, it should not be less than about 0.25 per cent to insure sound ingots. If 0.02 per cent of aluminum, titanium, calcium, zirconium, or barium is used, the silicon can be dropped to 0.10 per cent. Teeming temperature for ingots should be low and between 1480 to 1540°C. (2700 to 2800°F.). High teeming temperatures give ingots composed entirely of coarse dendritic grains which are hot short. In induction melting of these alloys, less gas trouble is encountered.

6. Melting Iron-nickel-chromium Alloys.—There is no essential difference in the melting practice for alloys containing higher nickel than chromium and for the higher chromium materials such as the 18-8 alloy. Molten chromium is oxidized in preference to iron, and in addition it has a strong affinity for carbon; most of the problems connected with the manufacture of iron-nickel-chromium alloys are, therefore, the same as in melting iron-chromium alloys and the 18 per cent chromium, 8 per cent nickel alloy. Part of the nickel, as the relatively pure metal or as high-nickel scrap, is added to the furnace at the beginning of the heat; the balance is added near the end of melting to make sure that specifications are met. Final deoxidation is made by ferromanganese and ferrosilicon as with most high-grade alloy steels, followed usually by a small amount of calcium.

In the literature on the melting of iron-nickel and iron-nickel-chromium alloys there are a number of recommendations for the addition of magnesium to the molten metal. This is supposedly necessary to eliminate the bad effect that small amounts of sulphur have on the malleability of these alloys. It is well known that magnesium is a valuable anti-sulphur malleablizer in non-

ferrous nickel alloys. According to Pilling,* by contagion, this usefulness of magnesium seems to have been carried over frequently in the literature to iron-nickel and iron-nickel-chromium alloys. Concerning the action of magnesium, Pilling stated:

The liquid solubility of magnesium in iron is so low and its vapor pressure at these temperatures is so high that its usefulness in this respect ceases at an iron content of about 20 per cent. If the attempt is made to introduce magnesium into melts richer in iron than this, the result is generally explosive, and apparently too small a fraction of the magnesium remains in the melt to be useful. Calcium, on the other hand, is very soluble in liquid iron and its action is the same as that of magnesium. An important limitation to its use is that, if too much is added, a low-melting-point constituent is formed, which is as damaging to malleability as is the sulphur which it is intended to neutralize. In general, a calcium addition of 0.02 to 0.06 per cent to a previously deoxidized bath is proper. There is a discussion of calcium versus magnesium in ferrous nickel alloys in U. S. Patent No. 1,824,966.

Iron-nickel alloys modified by chromium or other elements are ordinarily melted in the basic arc or induction furnace. Other than in Volume II of "The Alloys of Iron and Chromium" and the book by Thum[546] already mentioned, good general descriptions of melting methods have been published by Houdremont[344] for the basic electric and open-hearth processes, by Kerns[234] for the acid electric process, and by McKibben[459] and Hessenbruch and Rohn[489] for the coreless induction furnace.

According to Lake,[178] the electric-resistance alloys containing 60 to 70 per cent nickel, 15 to 20 per cent chromium, 15 to 20 per cent iron, and 1 to 3 per cent manganese are melted in small arc or in induction furnaces, using high-purity raw materials—ferrochromium which is very low in carbon or essentially carbon free, high-purity nickel, and 99.7 per cent iron are preferred. Carbon and other impurities should be kept to a minimum. Small amounts of carbon in the ferrochromium will burn out if the melt is held 1 hr. at 1540°C. (2800°F.). According to Russell,[360] English manufacturers of these alloys keep the manganese to 1 per cent or less, in contrast to American and Continental European manufacturers who add 1.5 to 3 per cent manganese.

There are relatively few published data on the manufacture of the high nickel-chromium-iron electric-resistance alloys; appar-

* Private communication, June 10, 1938.

ently the practice of melting and working these alloys is considered an important trade secret. An exception to this is the publication of full details in Russian.[463, 539] It is probable, however, that the described procedures are to be viewed as experimental in nature rather than as examples of the most satisfactory mill practice.

7. Casting Practice.—In general, iron-nickel, iron-nickel-chromium, and other modified iron-nickel alloys may be cast into any shape desired. Many of the alloys, however, especially the heat- and corrosion-resisting materials, have a number of inherent characteristics which make the foundry practice a specialized one calling for exceptional skill. These alloys have a narrow pouring range, a high shrinkage, and an unusually severe scouring action on the sand. Molds must, therefore, be carefully designed and made, and larger gates and more risers must be used than is customary for carbon and low-alloy steel castings. Generous fillets between heavy and light sections, the proper use of chills, and readily collapsible cores are necessary. Practical details of foundry practice, a complete discussion of which is hardly justified here, have been published by Lake,[178] Kayser,[261] Sutton,[267] Menough,[310], and Simonds.[323] According to the last named, the patternmakers' shrinkage for all of the high nickel and high nickel-chromium heat- and corrosion-resisting alloys is $\frac{5}{16}$ in. compared with $\frac{1}{4}$ in. per ft. for carbon steels and iron-chromium alloys.

D. MECHANICAL TREATMENT

Except for alloys of the 18-8 class there is little published information on the mechanical treatment of iron-nickel, iron-nickel-chromium, or other modified iron-nickel alloys. This is to be expected; many of these alloys are specialized products manufactured by relatively few industrial concerns, hence, as is customary with such products, mechanical working processes are closely held trade secrets. The few data on the mechanical treatment of iron-nickel alloys and of such modified iron-nickel alloys as fall within the field of the present monograph are summarized in the next three sections of this chapter.

8. Hot Working Iron-nickel Alloys.—Although Burgess and Aston[71] in 1909 determined the forging properties of a series of iron-nickel alloys containing between 0 and 100 per cent nickel,

their results are qualitative rather than quantitative and, since the publication of Yensen's data,[157,181] are primarily of historic interest.

The fact that ordinary iron-nickel alloys containing between 8 and 70 per cent nickel forge with difficulty at some temperatures and, in the case of alloys of certain compositions, do not forge at any temperature had been well known for some time; also well known was the fact that alloys of any composition could be made readily forgeable by the addition of a small amount of manganese.   Yensen, in his investigations of magnetic properties of these alloys, was faced with forging difficulties and so determined the effect of controlled additions of aluminum, carbon, magnesium, silicon, titanium, and manganese on the forgeability at the following temperatures:

Cold.....................	20 to 100°C. (70 to 210°F.)
Black.....................	below 600°C. (1110°F.)
Dull red.................	600 to 900°C. (1110 to 1650°F.)
Bright red...............	above 900°C. (1650°F.)

Most of the tests were carried out at a black and a dull red heat. As Yensen[181] noted in his paper, the forging operation, from a scientific standpoint, is crude at best, but the results were consistent enough to warrant the following conclusions:

1. At a dull red heat high-purity alloys containing less than 7 or 8 per cent nickel forge fairly well; with about 10 per cent nickel the forgeability is poor; but with about 15 per cent nickel it is good.   Alloys containing 20 per cent nickel forge poorly and with higher nickel content, up to about 70 per cent nickel, they do not forge at all.   Alloys containing more than 75 per cent nickel are readily forged.

2. Aluminum, carbon, and magnesium have no beneficial effect; the effect of silicon, if any, is slight.   This indicates that poor forgeability is not caused by oxides.

3. Manganese and titanium both improve forgeability.   The amount of either of these metals added should be about 2 per cent of the iron or the nickel whichever is the lesser; thus 0.8 per cent manganese should be added to either a 40 per cent or a 60 per cent nickel alloy, and 0.6 per cent to a 30 per cent or a 70 per cent nickel alloy.

If care is exercised in melting and if raw materials are relatively pure, iron-nickel alloys may be made forgeable without the

addition of manganese. This was noted by Elmen[297] who made forgeable alloys from ingot iron and electrolytic nickel. Pilling* made malleable iron-nickel alloys from ingot iron and shot nickel containing 30.3 and 68.9 per cent nickel, 0.05 per cent silicon, less than 0.01 per cent carbon, and less than 0.01 per cent manganese. These were deoxidized by silicon followed by the addition of 0.05 per cent calcium, which produced forgeability by eliminating the harmful effect of sulphur.

According to Strauss,[365] a satisfactory rolling temperature for alloys of the invar composition (containing about 36.5 per cent nickel and, of course, some manganese) is 1120 to 1150°C. (2050 to 2100°F.).

9. Hot Working Iron-nickel-chromium Alloys.—As long as the stainless iron-nickel-chromium alloys have been used industrially it has been known that these materials have a relatively narrow temperature range in which they may be readily rolled or forged, and that their resistance to deformation is several times that of carbon steels.

That this is a general characteristic of austenitic materials was suspected as long ago as 1925 by Mathews,[218] one of the pioneers in gamma-iron metallurgy. Mathews found that this narrow temperature range and difficulty of working were characteristic of alloys containing iron and approximately 30 per cent nickel, iron and 25 to 30 per cent chromium, and iron and approximately 28 to 30 per cent nickel plus chromium. Bain and Griffiths[249] found that for alloys containing 25 to 60 per cent nickel plus chromium the "temperature range for successful deformation was very narrow and very high."

Quantitative data on the resistance of iron-chromium-nickel alloys to deformation at rolling temperatures have been recently reported by Weddige[616] and by Pomp and Weddige.[608] Similar data were contributed by Lueg in a discussion of Weddige's paper. Although the data, which were obtained on small specimens and at low rolling velocities, may not be entirely applicable to conditions as they exist in a regular mill the fol-

* The results of a number of unpublished investigations obtained by N. B. Pilling and his associates at the Bayonne Research Laboratory were supplied for inclusion in this monograph through the courtesy of T. H. Wickenden, Assistant Manager of Development and Research, The International Nickel Company, Inc.

lowing conclusions seem to be of general application: " . . . increasing carbon (of carbon steels) increases resistance to deformation only up to rolling temperatures of about 900°C. (1650°F.); at higher temperatures, the resistance of a high-carbon steel is lower than that of the low-carbon steel. The high-alloy austenitic steels have a resistance several times greater than that of carbon steels, even at the highest rolling temperature . . . " In this connection Pilling* found that up to 1 per cent carbon has little effect on the hot-working properties of iron-nickel-chromium alloys except that it increases the stiffness at forging temperatures. Alloys containing 13 per cent nickel, 12 per cent chromium, and 0.4 and 1.0 per cent carbon forged excellently.

Hot-working temperatures of various iron-nickel-chromium alloys (excluding the 18-8 class) as recommended by four authorities are given in Table 1. Details of hot-working practice for the 18 per cent chromium, 8 per cent nickel class are given by Thum[546] and in Volume II of "The Alloys of Iron and Chromium." Most of the precautions noted in these two books are applicable to the iron-nickel-chromium alloys containing more nickel than chromium. Some of these may be summarized as follows: As temperature ranges for hot working are narrow, pyrometric control of heating is advisable. Ingots should be heated slowly to the preheating temperature, soaked thoroughly, and then heated to the rolling temperature; too much soaking at the latter should be avoided. The alloys scale slowly, but, if soaked too long at the rolling temperature, surface grain growth may occur and the susceptibility for surface cracking may be increased. Light drafts are recommended, with intermediate heating as necessary.

According to Pogodin and associates, [463] the nickel-chromium-iron electric-resistance alloys require, for successful hot rolling, comparatively many passes, light reductions, and frequent intermediate annealing. The temperature at the beginning of rolling should be 1150°C. (2100°F.). A 50-mm. (1.969-in.) ingot is reduced to 39 mm. (1.535 in.) by the first pass, to 30 mm. (1.181 in.) by the second, to 23 mm. (0.906 in.) by the third, and to 18 mm. (0.709 in.) by the fourth pass. After the fourth pass, reheating is necessary.

* See footnote, p. 13.

TABLE 1.—RECOMMENDED HOT-WORKING TEMPERATURES FOR IRON-NICKEL-CHROMIUM ALLOYS

Investigator	Approximate composition, per cent					Recommended hot-working temperatures		Remarks
	C	Mn	Si	Ni	Cr	°C.	°F.	
Strauss[365]	0.40	....	1	20	8	1010 to 1120	1850 to 2050	Preheat at 870 to 925°C. (1600 to 1700°F.)
	0.20	1.3	1.75	67	20	1095 to 1120	2000 to 2050	Soak thoroughly, reheat frequently
	0.50	1.12	2	38	18	1095 to 1120	2000 to 2050	Soak thoroughly, reheat frequently
	0.12	....	....	60	15	1175 to 1205	2150 to 2200	
	0.80	....	....	60	15	1000	1830	
Hondremont[344]	All austenitic alloys					1100	2010	
Metals Handbook[551]	0.25 max.	0.60 to 0.90	1.25 to 1.60	21 to 23	7 to 10	980 to 1120	1800 to 2050	Preheat at 870 to 980°C. (1600 to 1800°F.)
	0.25 max.	0.50 to 0.70	2.25 to 3.00	24 to 26	19 to 21	925 to 1120	1700 to 2050	
	0.25 max.	0.50 to 0.70	0.70 to 1.50	19 to 21	24 to 26	1120 to 1200	2050 to 2200	Preheat at 925 to 980°C. (1700 to 1800°F.)
Chambeyron[518]	....	....	....	25 to 60	15	900 to 1100	1650 to 2010	Reheat frequently, heating time about 10 hr. per ton

Russell[360] stated that it is practically impossible to roll cast ingots of the electric-resistance alloys; forging should be used for the preliminary roughing down. The ingots and the billets should be heated in a sulphur-free atmosphere, preferably an electric furnace.

10. Hot-working Properties of Complex Iron-nickel Alloys.— There are few specific data on hot-working practice for iron-nickel and iron-nickel-chromium alloys modified by other alloys. An anonymous author[372] gave the forging temperature of an alloy containing 15 per cent nickel, 14 per cent chromium, and 2 per cent tungsten as 1050 to 1100°C. (1920 to 2010°F.) and warned that it is necessary to stay within this range if good results are to be expected.

According to Hensel,[382] the addition of up to 20 per cent titanium to iron-nickel-manganese alloys containing about 15 per cent nickel and 10 per cent manganese causes red-shortness upon heating to 1250°C. (2280°F.) or above owing to a new phase which melts at these high temperatures. The best forging range for iron-nickel-manganese-titanium alloys is 1000 to 1100°C. (1830 to 2010°F.). Alloys containing more than 7 per cent titanium are especially prone to red-shortness.

An investigation by Kühlewein[499] on the iron-nickel-vanadium system included the forgeability of the alloys. Alloys whose composition lies near the low-nickel corner of the diagram (less than 40 per cent nickel) could not be hot worked if they contained more than 20 per cent vanadium. Alloys containing 15 per cent vanadium and any nickel content were workable; alloys with 20 per cent vanadium were workable if the nickel was less than 10 per cent, unworkable with nickel contents of 15 to 35 per cent, and workable with 40 per cent or more nickel.

In connection with a comprehensive investigation of the binary iron-nickel and the ternary iron-nickel-copper systems, Pilling* determined the forging properties of these alloys, using a 3500-lb. steam hammer, an initial forging temperature of 1200°C. (2190°F.), and rapid heavy blows. The alloys were melted in a high-frequency induction furnace using ingot iron, Monel metal, and supplemental additions of nickel and copper as required. To all the melts about 0.6 per cent manganese, 0.2 per cent silicon, and 0.02 to 0.04 per cent aluminum were added as deoxidizers.

* See footnote, p. 13.

To some of the melts 0.1 per cent magnesium, as a magnesium-nickel alloy (67 per cent magnesium), and 0.1 per cent calcium, as calcium metal or as a calcium-silicon alloy (25 per cent calcium), were added. Previous experience had indicated that a granular ingot from a cold melt forged somewhat better than a fibrous ingot from a hot melt, hence the ingots were poured at a temperature about 20°C. (35°F.) above the liquidus which
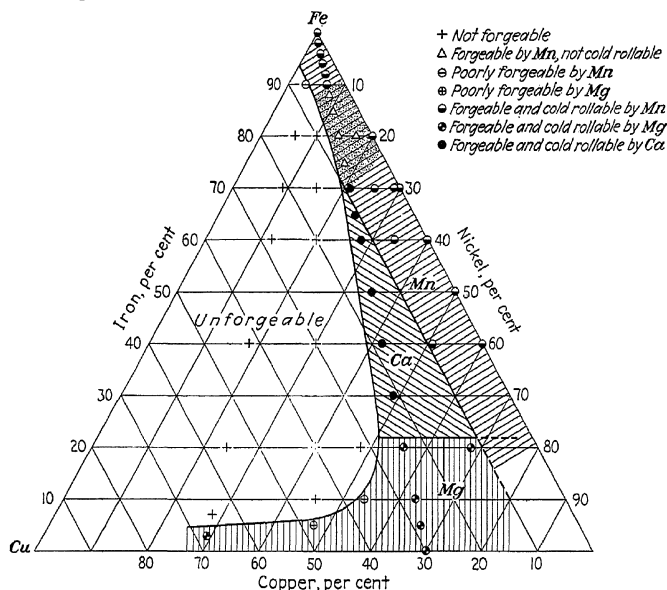
Fig. 1.—Composition versus forgeability of iron-nickel-copper alloys. (*Pilling, unpublished data, Research Laboratory, The International Nickel Company, Inc.*)

was determined for each melt. As poured the melts contained between 0.04 and 0.15 per cent carbon, 0.40 and 0.80 per cent manganese, and 0.005 and 0.40 per cent silicon. Sulphur contents were low, usually under 0.020 per cent.

Results of the forging tests are plotted in Fig. 1. From these data Pilling concluded:

1. The austenitic alloys of iron, nickel, and copper are workable hot with a nickel-copper ratio greater than 65 per cent nickel, and are, in addition, workable cold with a nickel-iron ratio greater than 23 per cent nickel. If properly melted, these

alloys have excellent forgeability and cold roll well without hardening excessively.

2. The treatment in melting necessary to insure satisfactory forgeability depends upon the iron and copper contents. The alloys deoxidized with manganese and silicon are forgeable when the copper is below 10 per cent or absent; if iron is less than 20 per cent, an additional treatment with magnesium is necessary for forgeability; and if copper is above 10 per cent and the iron above 20 per cent, magnesium is not effective and about 0.05 per cent calcium is required to give a workable metal.

Later work by Pilling on the effect of carbon on an alloy containing 34 per cent nickel, 6 per cent copper, remainder iron indicated that up to 1 per cent has little effect on the forging properties, notwithstanding the fact that of the 0.94 per cent total carbon present, 0.49 per cent was in the form of graphite. An alloy containing 0.33 per cent carbon showed less than 0.01 per cent graphite. The forging temperature for these alloys was 1170°C. (2140°F.).

Pilling also determined the forgeability of alloys containing more than 75 per cent iron and nickel, copper, and manganese in various high percentages. The results indicate that of the alloys containing 75 per cent iron all melts with nickel greater than 1.5 times the copper content were forgeable regardless of the manganese; this element apparently does not appreciably alter the critical nickel-copper ratio in the iron-nickel-copper alloys discussed before. A series of iron-nickel-manganese alloys, with 75 to 89.3 per cent iron, 5.5 to 21.0 per cent nickel, 1.1 to 12.7 per cent manganese, and 0.03 to 0.17 per cent carbon forged satisfactorily. In addition to the manganese present, 0.20 per cent silicon and 0.02 per cent aluminum were used as deoxidizers. The initial forging temperature for these alloys was 1140 to 1190°C. (2085 to 2175°F.).

11. Cold Working Iron-nickel and Iron-nickel-chromium Alloys.—Like other austenitic alloys the iron-nickel alloys containing more than 25 to 30 per cent nickel are readily cold rolled or cold drawn. As they harden more rapidly by cold work than the carbon or low-alloy steels, they must be softened frequently during cold working by air or water cooling from a high temperature. Grain growth in these alloys is not serious if they are heated below 1040°C. (1900°F.).

Cold-working practice for austenitic alloys of the 18-8 class and the effect of cold working on the properties is the subject of an extensive literature which has been reviewed in detail in Volume II of "The Alloys of Iron and Chromium." In general, the austenitic iron-nickel-chromium alloys work harden rapidly; frequent softening is necessary in the commercial production of strip, tube, and wire. Before austenitic alloys are cold worked they are commonly softened by water quenching (or, in the case of thin sections, by air cooling) from approximately 1000 to 1150°C. (1830 to 2100°F.) to insure that the structure is entirely austenitic. During the cold-working operation this softening treatment is repeated as often as necessary; according to Thum,[546] it becomes necessary for strip, after a reduction of 10 per cent in gage, for tubes, after a reduction of about 20 per cent in cross-sectional area, and for wire, after a reduction of 65 per cent in diameter.

A number of investigators, especially Pilling,[358] have determined the effect of nickel on the work hardening of the austenitic iron-nickel-chromium alloys. As an example, the effect of nickel on the work hardening of alloys containing 0.08 to 0.10 per cent carbon and 18 per cent chromium as determined by Pfeil and Jones[462] is shown in Table 2. The alloys were softened by water quenching from 1150°C. (2100°F.) before cold rolling.

The same investigators found that nickel has also a pronounced effect upon the work hardening as influenced by the carbon.

TABLE 2.—EFFECT OF NICKEL ON WORK HARDENING OF AUSTENITIC IRON-NICKEL-CHROMIUM ALLOYS CONTAINING 0.08 TO 0.10 PER CENT CARBON, 18 PER CENT CHROMIUM, AND VARIABLE NICKEL*

Reduction in thickness by cold rolling, per cent	Brinell hardness for a nickel percentage of			
	8	12	15	29
0	180	150	135	125
10	275	230	200	185
20	340	275	250	225
30	395	320	295	250
40	435	345	320	270
50	465	365	335	285

* Pfeil and Jones.[']

In the ordinary 18-8 alloy, an increase in carbon from 0.04 to 0.10 per cent increases the Brinell hardness number of a 50 per cent cold-rolled alloy from 410 to 465. When the nickel is increased to 15 per cent, increasing the carbon from 0.05 to 0.20 per cent increases the Brinell number from 340 to 360. Pfeil and Jones also studied the effect of molybdenum, silicon, and titanium on the work-hardening properties of the 18-8 alloy.

The high-nickel iron-nickel-chromium electric-resistance alloys are cold drawn into wire and cold rolled into tape. For wire drawing Russell[360] recommended diamond dies of the highest quality. The metal must be homogeneous for successful wire drawing, and much slower speeds are used than are common for iron and copper wire.

As mentioned in the previous section, alloys of iron, nickel, and copper which have a nickel-iron ratio greater than 23 per cent nickel cold roll well without hardening excessively. The compositions of these alloys are given in Fig. 1. This assumes, as stated on page 17, that the alloys are properly deoxidized by manganese, magnesium, or calcium. The only difficulties encountered by Pilling* in cold rolling the forgeable alloys were with those in which martensite formed upon air cooling, especially the ones containing between 10 and 30 per cent Monel metal, i.e., 7 per cent nickel and 3 per cent copper, and 21 per cent nickel and 9 per cent copper.

Some of Pilling's iron-nickel-manganese alloys (three of which contained copper), although normally austenitic, hardened excessively by cold work, in a manner similar to the well-known behavior of high-manganese steel. These alloys had the following composition:

Alloy No.	Composition, per cent				
	Fe	Ni	Mn	Cu	C
404	85.0	Trace	14.2	...	0.22
702	82.0	...	19.8	...	0.2
412	82.5	5.6	11.5	...	0.11
403	82.5	2.6	13.1	1.3	0.15
409	80.0	5.5	10.8	2.7	0.15
390	75.0	7.0	14.2	3.0	0.18

* See footnote, p. 13.

As an approximation, Pilling found that excessive hardening by cold work in low-carbon austenitic high-manganese iron-nickel-manganese alloys can be substantially avoided if a nickel content is provided which is at least 0.7 per cent of the manganese content.

In general, Pilling concluded that the maximum manganese content consistent with good working properties in marginal austenitic alloys is about 9 per cent. With this amount the nickel can be reduced from 26 per cent to about 10 per cent and the alloy will still be austenitic. Carbon, however, produces extreme work hardening in the marginal austenitic alloys containing manganese, hence it is necessary to use low-carbon ferromanganese in their manufacture.

E. AUTHOR'S SUMMARY

1. Although meteoric iron, containing nickel, was one of the earliest metallic materials used by man, nickel was not recognized as a metal until about the middle of the eighteenth century, and the industrial use of nickel as an alloy with iron did not begin until less than 50 years ago. Today nickel is one of the most widely used of the alloying elements.

2. Metallic meteorites consist mostly of iron and nickel; there are commonly three constituents, *kamacite*, an alpha-phase alloy; *taenite*, a gamma-phase alloy; and *plessite*, a mixture of the two. The characteristic structure of meteorites is Widmanstätten which has been known for more than a century and has been investigated frequently. The Widmanstätten structure results from the precipitation of alpha-phase plates from the large gamma-phase grains upon cooling.

3. Iron-nickel alloys may be melted in open-hearth, electric, or induction furnaces. A basic electric furnace with the usual slag practice for high-grade steels is ordinarily used. Iron-nickel alloys melted in the arc furnace dissolve large quantities of various gases which can be eliminated only by saturating the bath with carbon monoxide which, in turn, is removed by deoxidizing with a carbide slag and the addition of silicon or other final deoxidizer. In induction melting, there is less gas absorption.

4. The melting practice for iron-nickel-chromium alloys containing more nickel than chromium is essentially the same as the

practice used for the 18 per cent chromium, 8 per cent nickel alloy, which is discussed in another monograph.   Final deoxidation with ferromanganese and ferrosilicon, as in all high-grade alloy steels, is frequently followed by a small amount of calcium.

5. Iron-nickel and iron-nickel-chromium alloys can be readily cast into a variety of shapes.   The alloys have in general a narrow pouring range and a severe scouring action on the sand. Molds must, therefore, be carefully designed and gated.   The patternmakers' shrinkage is $\frac{5}{16}$ in. compared with $\frac{1}{4}$ in. per ft. for carbon and most low-alloy steels.

6. All high-purity iron-nickel alloys are forgeable provided some care is exercised.   Less pure alloys are forgeable upon addition of manganese or titanium; a recommended addition is about 2 per cent of the nickel or iron content, whichever is the smaller.

7. Austenitic iron-nickel-chromium alloys are readily hot worked at temperatures of approximately 1000 to 1120°C. (1830 to 2050°F.).   As for most austenitic alloys, the temperature range for hot working is narrow and the alloys have a resistance to hot deformation which is several times that of carbon steels.   It is common practice to preheat these materials, soaking thoroughly at the preheating temperature, and finally heating rapidly to the rolling temperature; too long soaking at that heat should be avoided.   Carbon up to 1 per cent has little effect on the hot-working properties of iron-nickel-chromium alloys except for some increase in the stiffness at rolling temperatures.

8. The useful austenitic alloys of iron, nickel, and copper, if properly melted, have satisfactory hot-working properties provided the nickel-copper ratio is greater than 65 per cent nickel.   Up to 1 per cent carbon has little effect despite the fact that much of the carbon graphitizes.   If the nickel in these alloys is more than 1.5 times the copper content and the iron more than 75 per cent, manganese additions have practically no effect on the hot-working properties.   If the composition is such that no martensite forms on air cooling, these iron-nickel-copper and iron-nickel-copper-manganese alloys can be cold worked without hardening excessively.

9. Iron-nickel and iron-nickel-chromium alloys are readily cold worked.   They harden more rapidly than carbon or low-

alloy steels and must, consequently, be softened frequently by air or water quenching from a high temperature. Increasing the nickel in an iron-nickel-chromium alloy decreases to a marked degree the hardening by cold working. Data are quoted which show that in a low-carbon alloy containing 18 per cent chromium and 8 per cent nickel a reduction of 50 per cent by cold rolling increases the Brinell hardness number from 180 to 465, while in an alloy containing the same carbon and chromium but 29 per cent nickel the hardness increase is from 125 to 285 Brinell. Nickel also makes the influence of carbon on the work hardening much less pronounced.

CHAPTER II

THE IRON-NICKEL SYSTEM

The High-temperature Portion of the Diagram—The Low-temperature Portion of the Diagram—Author's Summary

In principle, the iron-nickel phase diagram is one of the simplest of the ferrous binary diagrams. Over certain ranges of temperature, iron and nickel are completely intersoluble and, as will be demonstrated, these elements seemingly exhibit no tendency toward compound formation. Hence, there is no question about the qualitative nature of the high-temperature portion of the diagram, although the location of the phase boundaries is yet to be established with precision.

The position of the low-temperature portion of the diagram is not so secure. Nickel depresses the temperature of alpha-gamma transformation sufficiently in some instances to render transformation either impossible or of very low velocity; consequently there is doubt whether equilibrium solubility curves exist for certain ranges of concentration and temperature. Intimately connected with the question is the well-known "hysteresis" of nickel steels of the so-called "irreversible" class. These terms are defined on page 32.

Another of the interesting features of the iron-nickel system is the fact that these elements are both ferromagnetic at ordinary temperatures. Strictly speaking, of course, the phase diagram is not concerned with the magnetic properties of its phases. However, some of the early investigators confused magnetic inversions with phase transformations, consequently it is impossible to ignore magnetic inversions while reviewing the literature. Further, many iron-nickel alloys derive their practical importance from the very fact that they are ferromagnetic.

In the past, interpreters of the unusual properties of iron-nickel alloys turned often to existing diagrams or invented new ones in order to explain everything from the structure of meteorites to the high permeability of some alloys. Some of these

diagrams were no less ingenious than the interpretations which they supported, but most of them are impossible in the light of more recent knowledge. For this reason, the present knowledge of the diagram will be presented before entering upon a historical review.

A. THE HIGH-TEMPERATURE PORTION OF THE DIAGRAM

The high-temperature portion of the iron-nickel diagram, it was said, is known qualitatively with certainty. The liquidus is continuous except for a peritectic transformation that originates from the fact that iron freezes in the body-centered cubic form, whereas nickel freezes in the face-centered cubic form.

12. Peritectic-transformation Region.—The first investigation of the liquid ⇌ solid equilibria of iron-nickel alloys, as is true of so many metallic systems, was performed in Tammann's laboratory. Results were reported in 1905 by Guertler and Tammann.[60] These data were followed by those of Ruer and Schüz[87] in 1910. Because, however, of the fewness of the alloys examined and of the crudities of technique of those days, the peritectic transformation was not then discovered, although it seems possible that it might have been had Ruer and Schüz investigated a few alloys in the 0 to 10 per cent nickel range. Ruer's work on the peritectic region of ferrous binary systems appeared in 1914. The first investigation utilizing materials and methods which could promise fairly reliable data was conducted by Hanson and Freeman.[188] These workers prepared alloys from ingot iron and nickel shot of composition as given in Table 3. The crucibles were enclosed by muffles to prevent contamination by carbon from the "carbon-ring" furnace. A purified-nitrogen atmosphere was used to prevent oxidation. No difficulty was found in producing homogeneous ingots, even without stirring the melt. These ingots were subsequently subjected to thermal analysis.

Inasmuch as the peritectic transformation of the iron-nickel system occurs in the vicinity of 1500°C., considerable difficulty was encountered in securing satisfactory thermal data. Further, most of the melts were subject to undercooling, but this was overcome by inoculation. The data finally secured by special technique were thought by Hanson and Freeman to be subject to error no greater than 2°C. These will be examined shortly.

In 1925, Vogel[225] reported an investigation of the structure of meteoric iron which included a determination of the peritectic region. Alloys were prepared under hydrogen from the "purest electrolytic iron" and nickel containing "traces of cobalt." In the same year Kasé[215] reported a few thermal data but superseded them two years later with data on alloys, melted

TABLE 3.—COMPOSITION OF COMPONENT METALS USED BY INVESTIGATORS OF TEMPERATURES OF LIQUID-SOLID EQUILIBRIA

Investigator	Year	Metal	Composition, per cent							
			Fe	Ni	C	Mn	S	Co	Al	Cu
Ruer and Schüz[87].........	1910	Nickel			0.19					
		Iron				0.01	0.06	0.01	0.01	0.03
Hanson and Freeman[188]...	1923	Nickel		99.98						
		Iron			0.012	0.017	0.07	0.017	0.014	
	1925	Nickel	"Containing a trace of cobalt"							
		Iron	"Purest unannealed electrolytic"							
	1927	Nickel	0.10		0.37	0.006	Trace	0.019	Trace	Trace	Trace	0.013
		Iron		0.03	0.01	0.02	0.023	0.008		Trace	
Bennek and Schafmeister[374].	1931	Nickel	99.8	0.08		0.01	Trace	0.05	Trace	Trace
		Iron		0.02	Trace	Trace	0.01	0.023	Trace	0.

under hydrogen, of iron and nickel of composition given in Table 3. For the moment, it suffices to state that the results of Hanson and Freeman, of Vogel, and of Kasé leave something to be desired by way of concordance. This fact seemingly led Bennek and Schafmeister to reinvestigate the peritectic region.

Bennek and Schafmeister[374] alloyed iron and nickel, of composition given in Table 3, under an atmosphere of hydrogen. The melts were held at 1570°C. for some time, then subjected to several cooling-heating cycles over the 1570 to 1350°C. range for thermal analysis. The thermocouple was calibrated at frequent intervals to insure accuracy. Before turning to the actual data, several observations may be recorded.

It is of interest to note that Bennek and Schafmeister observed no appreciable effect of cooling rate (0.17 to 2°C. per sec.) on transformation temperature. Of more interest, however, is the fact that temperatures of transformation obtained upon cooling

agreed well with those obtained upon heating; this indicates approach to equilibrium values.

Available data on the peritectic region of the iron-nickel diagram are assembled in Table 4 and shown graphically in Fig. 2. It is clear that the only thing proved conclusively is that three-phase ($\delta + \gamma + L$) equilibrium exists and that it is of the peritectic type. Consequently, the curves were drawn in that manner, giving most weight to the data of Bennek and Schaf-
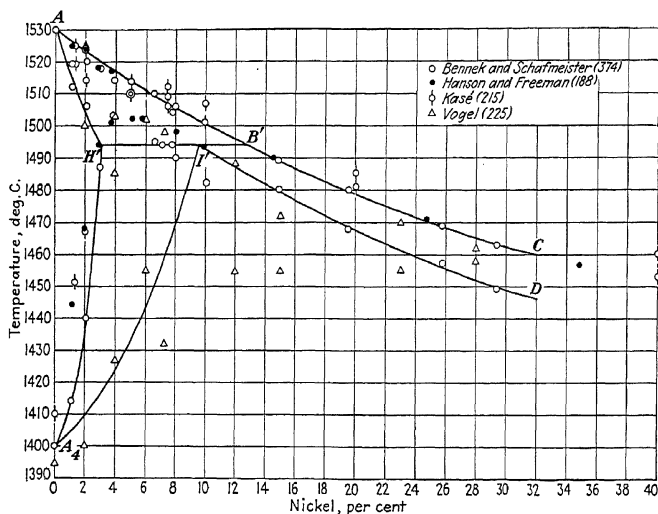
FIG. 2.—The peritectic region of the iron-nickel diagram.

meister. From the nature of thermal analysis, the two branches of the liquidus, AB' and $B'C$, should be most trustworthy, and this expectation is fulfilled by the data which should be most accurate; *viz.*, those of Hanson and Freeman and of Bennek and Schafmeister, for it is to be seen that their data are in satisfying agreement. (The question of the melting point of iron need not be entered upon; the value given is consistent with curve AB'. Any selected melting point depends upon the points chosen for thermocouple calibration.) There is less certainty about solidus curves AH' and $I'D$, as is to be expected. It is known, however, that the temperature interval between $B'C$ and $I'D$ is small; hence, $I'D$ may be considered to be known with more certainty

TABLE 4.—LIQUID-SOLID EQUILIBRIUM DATA

Investigator	Nickel content of alloy, per cent	Thermal points, °C., recorded on				
		Cooling			Heating	
		First effect		Second effect	First effect	
		Began	Ended		Began	Ended
Ruer and Schüz[87]....	0	1502				
	10	1489				
	20	1472				
	30	1460				
	40	1448				
	50	1441				
	60	1437				
	.70	1435				
	80	1441				
	90	1444				
	100	1451				
Hanson and Freeman[188]............	0	1530	....	1400		
	1.14	1525	....	1444		
	1.98	1524	....	1468		
	2.89	1518	....	1494		
	3.74	1517	....	1501		
	5.09	1502				
	5.80	1502				
	8.02	1498				
	9.96	1493				
	14.6	1490				
	24.7	1471				
	34.8	1457				
	45.1	1446				
	54.6	1440				
	59.3	1439	....	1434		
	65.1	1436	....	1432		
	66.7	1436				
	69.3	1436	....	1431		
	74.5	1437	....	1433		
	79.2	1442				
	84.2	1444				
	89.1	1450				
	100	1452				

TABLE 4.—LIQUID-SOLID EQUILIBRIUM DATA.—(*Continued*)

Investigator	Nickel content of alloy, per cent	Thermal points, °C., recorded on				
		Cooling			Heating	
		First effect		Second effect	First effect	
		Began	Ended		Began	Ended
Vogel[225]	0	1530	....	1395		
	2	1525	1500	1400		
	4	1503	1475	1427		
	6	1502	....	1445		
	7.3	1498	....	1432		
	12	1488	....	1455		
	15	1472	....	1455		
	23	1470	....	1455		
	28	1462	....	1458		
Kasé[260]	0	1530	....	1410		
	1.3	1525	1519	1451		
	2	1524	1514	1467		
	5	1514	....	1510		
	7.5	1512	1506	1509		
	10	1507	1501			
	20	1485	1481			
	40	1460	1453			
	60	1444	1438			
	80	1445	1440			
	100	1452				
Bennek and Schafmeister[374]	1.1	1519	1512	1414		
	2.06	1520	1506	1440		
	3.0	1518	....	1487		
	3.9	1514	1503			
	6.6	1510	1495	....	1494	1508
	7.1	1508	1494			
	7.8	1504	1494	....	1494	1508
	8.0	1506	1490			
	10.0	1501	1482			
	14.85	1489	1480	....	1482	1491
	19.5	1476	1469	....	1468	1484
	19.9	1480	1472	....	1467	1479
	25.7	1469	1459	....	1455	1469
	29.3	1461	1448	....	1450	1465
	49.2	1438	1429	....	1424	1438

than the solidus of some other systems. The position of AH'
is difficult to determine experimentally. The curve shown,
however, is consistent with the data of Bennek and Schafmeister
and, assuming the estimated location of point H' to be reasonable,
cannot be far wrong. The A_4H' boundary of the delta phase
was drawn giving most weight to the data of Bennek and Schaf-
meister; considering the concentration range, it is to be seen that
the points of Hanson and Freeman and of Kasé agree fairly well.
The location of boundary A_4I' depends entirely upon the location
of point I', since A_4I' has not been determined experimentally.
Point I' in turn depends upon the temperature of non-variant
equilibrium, represented by $H'I'B'$. The temperature shown,
1494°C., is perhaps somewhat low but is consistent with the
remainder of the construction. Hanson and Freeman selected
1502°C. for $H'I'B'$, whereas Bennek and Schafmeister chose
1497°C. The 5°C. difference may be considered to be satis-
factory agreement. The 1494°C. value is selected here because
Bennek and Schafmeister obtained that value on *heating* as well
as on cooling, although the importance here of points obtained
on heating is debatable. Even so, there is a spread of only
8°C.—1494 to 1502°C.—surely of small significance in the
vicinity of 1500°C.

The data of Vogel, even though consistent among themselves,
deviate so violently from the others (*e.g.*, a temperature of
1455°C. for that of non-variant equilibrium) that they have
been given no weight. Similarly, the data of Kasé seem to be
doubtful.

To improve the certainty of Fig. 2, the available data on
$H'I'B'$ must be checked experimentally. However, the accuracy
of this portion of the diagram is probably great enough for
ordinary purposes. To summarize, the liquid-phase boundary
is known with reasonable accuracy, as is the lower boundary of
the delta phase. The temperature interval between the liquidus
and solidus at temperatures below that of non-variant equilibrium
is so small that appreciable error is unlikely. The uncertainty
of temperature of non-variant equilibrium is not appreciable,
but it is felt more because of the concomitant relatively large
uncertainty of the concentration values of points H', I', and B'.

13. Remainder of the High-temperature Portion.—The mate-
rials and methods of investigators of the remainder of the liquid

⇌ solid equilibria of the iron-nickel system were described in the preceding section. Their data are assembled in Table 4 and Fig. 3. Bennek and Schafmeister[374] unfortunately did not extend their study to the nickel-rich alloys but, where there is duplication, agreement with the findings of Hanson and Freeman[188] is excellent. This lends great weight to the remainder of the points of the latter. In addition, the points of Ruer and Schüz seldom diverge by more than 3°C.; hence, the liquidus curve may be considered well established. Again, by virtue of the narrow temperature interval, the solidus cannot be much
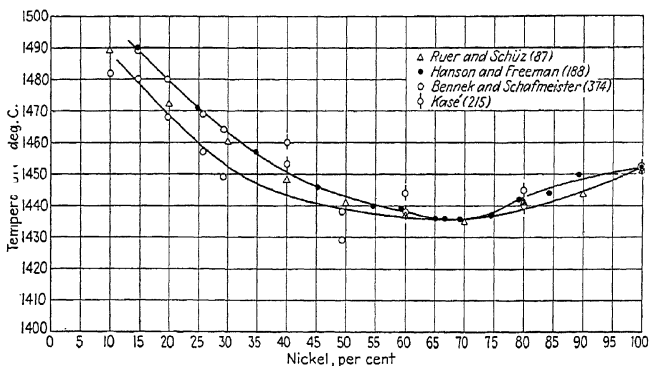
FIG. 3.—The remainder of the high-temperature region of the iron-nickel diagram.

in error, although it cannot be regarded as satisfactorily established experimentally. The most outstanding feature of this portion of the diagram, first observed by Guertler and Tammann,[60] is the temperature minimum of the solidus-liquidus curves at about 68 per cent nickel and 1436°C.

Thus, the high-temperature portion of the iron-nickel diagram is simple. Were it not for the existence of the delta polymorph of iron, the liquidus and solidus would be those characteristic of two completely intersoluble components exhibiting a tendency toward incomplete intersolubility (therefore, the tendency opposite to that of compound formation[534]). The peritectic transformation arises from what may be considered to be the limited intersolubility of delta iron and nickel.

B. THE LOW-TEMPERATURE PORTION OF THE DIAGRAM

Because of certain of their properties, iron-nickel alloys are important over a wider range of concentration than perhaps any other binary alloys of which iron is one component. This has resulted in an extraordinary amount of investigation of their constitution. Even though simple in principle, so far as phase boundaries of the diagram are concerned, the behavior of the alloys is often complex, *i.e.*, not perfectly understood.

Most of the alloys of commercial importance, such as those of low coefficient of thermal expansion and those of high magnetic permeability, exist in the gamma phase, which is characteristic of iron at certain high temperatures and of nickel at all temperatures below that of melting. In one sense, therefore, the boundaries of the alpha and gamma phases are unimportant. (Hexagonal nickel has been reported, but seemingly always as a result of some special treatment, such as cathode sputtering; see, for example, Bredig and von Bergkampf.[376])

The first attempts to locate the boundaries of the alpha and gamma phases were made in order to be able to interpret the microstructure of meteorites. Results of these attempts are examined later.

14. The Schematic Iron-nickel Diagram.—In order to review the nature of the low-temperature phase boundaries to be discussed, Fig. 4 was constructed. It is to be seen that, excluding the broken lines *bcd* and *efg*, which represent magnetic inversions, the low-temperature portion of the iron-nickel diagram contains only two phase boundaries. The line of onefold saturation of gamma phase is represented by *adfj*, that of onefold saturation of alpha phase by *aceh*. The two one-phase regions are, as usual, separated by a two-phase region. The magnetic-inversion line *bcd* is of small importance, if any. Line *efg*, on the contrary, is of major importance.

15. Irreversibility.—Iron-nickel alloys capable of undergoing alpha-gamma transformation were dubbed irreversible because, for any one alloy, the alpha-gamma transformation cannot be made to proceed at even approximately the same temperature as the gamma-alpha transformation—at least by ordinary methods. (The phenomenon of irreversibility, or hysteresis, seems to have been discovered in 1890 by LeChatelier,[13] who

thought that it was caused by oxidation of silicon.) The divergence of apparent transformation temperatures increases rapidly as the nickel concentration is increased. The methods used most frequently to attempt to determine the transformation temperatures have been thermal analysis and dilatometry. Since both, as ordinarily used, depend upon finite rates of heating or cooling, it is to be expected that each is most effective at indicating the temperature at which the rate of transformation is greatest. This temperature, it is clear, may be far from the equilibrium temperature.
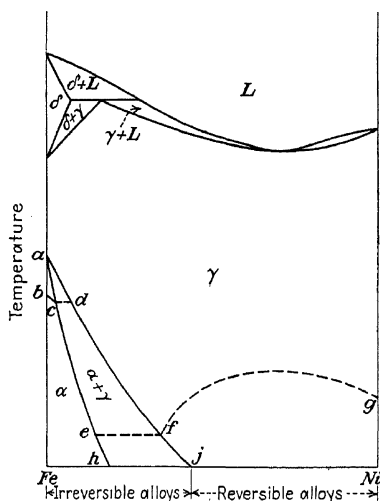
FIG. 4.—The schematic iron-nickel diagram.

For some reason, it is the usual observation that there is considerably less resistance to alpha-gamma transformation than to transformation in the reverse direction. This transformation therefore proceeds more rapidly; hence, the so-called *Ac* points, as determined by thermal analysis or dilatometry, are often nearer the equilibrium values than are the *Ar* points.

As nickel is increased, a range of concentration is finally reached for which the normal transformation (*i.e.*, one preceded by diffusion) does not occur; if the temperature is reduced to accelerate transformation, the gamma phase breaks down, but to a

rapidly formed martensite-like product. It is conceivable that after a lapse of time (perhaps estimated in geologic units) an equilibrium structure would result from diffusion. For practical purposes, however, there is no equilibrium temperature.

If it were possible to prepare such iron-nickel alloys in the alpha form, it might be possible to learn something about the equilibrium temperatures by approaching the transformation from below. This is impossible, for these alloys freeze in the gamma form.

A picture of the enormous lengths of time required for atoms to fall into equilibrium positions at low temperature is afforded by
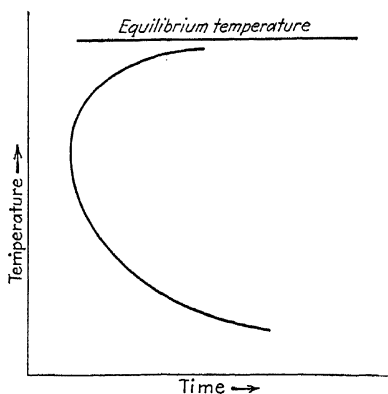
Fig. 5.—The time-temperature curve of the gamma-alpha transformation of iron.

some computations of Bragg and Williams[477] on "relaxation time," *i.e.*, the time required by an alloy to relax to equilibrium. For example, if relaxation time is 1 sec. at 500°C., 1 hr. is required at 350°, several days at 270°, and 30,000 years at 200°.

16. Temperature Coefficient of the Gamma-alpha Transformation.—If the time required for the gamma-to-alpha transformation of iron is plotted against temperature, a curve of the type shown in Fig. 5 results. This curve may be considered as the resultant of two factors for which the temperature coefficients are not the same. These factors, as a first approximation, may be assumed to be: (1) The driving force of the transformation, which is properly measured by the change of free energy, or

"thermodynamic potential," (ΔG) of transformation.* This is of zero value at the equilibrium temperature but increases rapidly as temperature is reduced. (2) The resistance to transformation; this also increases rapidly as temperature is lowered. At a temperature immediately below the equilibrium value, the resistance is relatively low, but the free energy is also of small value; the result is that transformation proceeds slowly. Upon further reduction of temperature, both factors are increased in value, but at first the free energy increases more rapidly than the resistance; consequently, the transformation proceeds more rapidly. At lower temperatures, however, the resistance increases in value more rapidly than does the change of free energy, with the result that the transformation proceeds more and more slowly. It is clear that there is a certain temperature for which the transformation proceeds most rapidly, as is shown by Fig. 5.

Rates of transformation of steels were analyzed by Austin[512] on the basis of the foregoing. Existing free-energy data on iron are not very accurate, and there is no simple way of measuring the resistance factor, but assumed simplified forms of the temperature coefficients of the two factors led to verification of the general validity of the concept.

It may be deduced at once, therefore, that the addition of nickel to iron would increase the time required for transformation. Since nickel decreases the temperature of gamma-to-alpha transformation, increased nickel content transfers the equilibrium temperature to temperatures at which resistance to transformation is increasingly great. The increase of resistance probably involves two factors: (1) the increase of resistance upon reduction of temperature and (2) the increase of resistance upon change of concentration. Since the nickel atom is very similar to the iron

* These assumptions might be challenged by many chemists unfamiliar with the metallic state, as may be inferred from the following statement taken from a book review by E. A. Guggenheim (*Trans. Faraday Soc.*, v. 32, 1936, p. 523): "This work . . . is, in the reviewer's opinion, marred by the attempt to apply thermodynamics to chemical kinetics. All progress in this field has come from considerations of molecular mechanism, and the idea that a reaction rate is determined by the affinity of the reaction and a chemical 'viscosity' is probably admitted to be abortive by all chemists except the De Donder school." The reasoning applied to solid metals, however, does not seem to be characterized by abortiveness.

atom, it is probable that the rate of diffusion of nickel in iron is very low; hence, the resistance to transformation is inherently high.

There are no data on iron-nickel alloys which would permit computation of rates of transformation. It may be deduced from certain experimental observations, however, that, excepting the alloys of lower nickel content, there is no possibility of transformation at temperatures near the equilibrium temperature in practicable time. Herein, it may be inferred, lies the reason for the phenomenon of "irreversibility."

17. Effect of Purity on the Transformation Rate of Iron-nickel Alloys.—Hanson and Hanson[149] (see page 46) concluded from their investigation of iron-nickel alloys that the alpha-gamma transformation is accelerated by the presence of impurity. They also quoted Guillaume, who stated to them that "carbon, even in very small quantities, has a marked effect on iron-nickel alloys, and renders them much more liable to undergo changes."

18. Nature of the Martensite-like Transformation.—That diffusion plays no part in the martensite-like transformation of gamma to alpha phase at low temperatures was proved by Scheil,[432] who worked with a 29 per cent nickel alloy. This alloy transformed at high velocity at all temperatures at which it would transform at all. The only effect of increased cooling rate was to increase the fraction transformed; this result is clearly incompatible with transformation involving diffusion. Only transformation by shear is possible. Scheil considered two hypotheses:

1. A minimum shear stress is necessary to start the transformation.

2. Transformation can occur in stress-free gamma phase. This demands a mechanically unstable state for transformation.

Both hypotheses imply that transformation is favored by stress; this is an experimental fact. In fine-grained material, however, the hindering effect of grain boundaries exceeds the favoring effect of stress, hence, hypothesis 1 is untenable. Hypothesis 2 fits the facts.

Hypothesis 2 demands that the modulus of elasticity become zero at the transformation temperature. Scheil observed it to decrease near the transformation.

Dehlinger[481] showed that, even though the microstructure of an iron-nickel alloy which has undergone the high-velocity transformation is similar to that of a martensitic carbon steel, there is an important difference. X-ray analysis proved the iron-nickel-alloy constituent to be body-centered cubic in structure, whereas martensite is tetragonal. The similarity of microstructure arises from the fact that the mechanism of precipitation from the gamma phase is similar.

19. Scheil's Dilatometric Study. For study of transformation behavior of iron-nickel alloys, Scheil[540] used an alloy containing 4.8 per cent nickel and 0.04 per cent carbon. The investigation differed from the usual in that dilatation at various constant temperatures as a function of time was measured (Figs. 6 and 7). These data are included in Fig. 8, which shows the dilatation curve for ordinary rates of heating and cooling. It is to be seen that the interval of irreversibility became narrower as the time increased. Further narrowing could have been obtained by using still longer testing periods; hence, the interval of irreversibility of this alloy is merely an interval of slow transformation.

FIG. 6.—Progress of the isothermic alpha-gamma transformation of a 4.8 per cent nickel iron-nickel alloy. (Scheil.[540])

In another series of tests, the alloy was held at various temperatures within the irreversibility interval sufficiently long for isothermic transformation (as indicated by change of length) of one-third of the alloy (initially in the alpha phase); it was then cooled to room temperature, then reheated. In still other tests, heating was continued immediately after isothermic partial transformation. Several of the resulting curves are shown in Fig. 9. From curve *a* it is seen that, after partial transformation
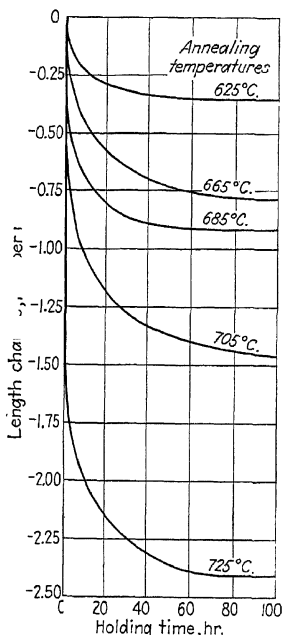
at 685°C., the gamma-alpha transformation (indicated by expansion) began at 460°C.; this is considerably lower than the
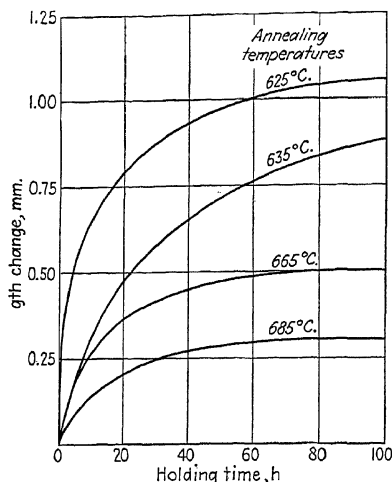
FIG. 7.—Progress of the isothermic gamma-alpha transformation of a 4.8 per cent nickel iron-nickel alloy. (*Scheil.*[540])
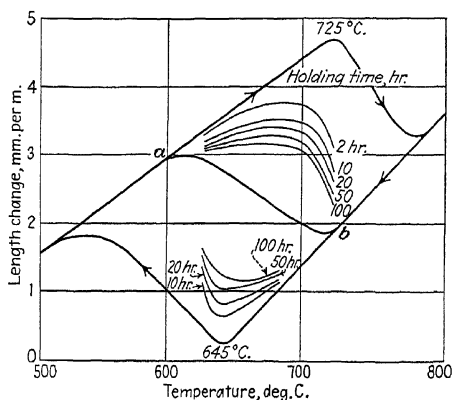
FIG. 8.—Variation of dilatation, with time of holding at constant temperature, of a 4.8 per cent nickel iron-nickel alloy. (*Scheil.*[540])

ordinary value of 645°C. (Fig. 8). Upon reheating, as shown by curve *b*, the alpha-gamma transformation (indicated by contraction) took place in two steps; the temperature of gamma-

alpha transformation, it is to be seen, deviated less from the ordinary value. The deviation vanished in subsequent cycles of heating and cooling. From curve c it is to be seen that, upon further heating after partial alpha-gamma transformation at 685°C., the remaining portion of alpha phase began to transform at 760°C.; the ordinary temperature was 725°C. (Fig. 8). Upon subsequent cooling, the gamma-alpha transformation took place in two steps.
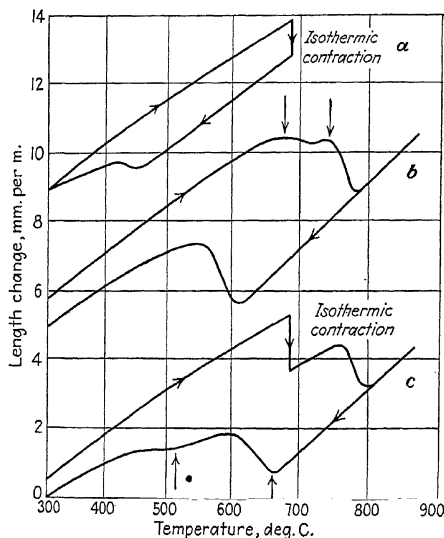
FIG. 9.—Variation of dilatation, on cooling and heating after annealing at various temperatures, of a 4.8 per cent nickel iron-nickel alloy. (*Scheil*.[540])

Data on the alloy after partial isothermic transformation are collected in Table 5. The two-stage transformations indicate that isothermic transformation involves change of nickel content, as is required by theory. It is to be seen that the transformation temperature of the residual alpha phase was increased by increase of temperature of isothermic alpha-gamma transformation. This indicates increased change of nickel content, but this is probably to be ascribed more to the larger proportion of transformed gamma phase than to the higher temperature. The increased transformation temperature of the residual alpha phase means impoverishment in nickel. This is substantiated by the corre-

sponding increase of temperature of the first stage of gamma-alpha transformation upon subsequent cooling. The second stage, however, according to Scheil, should be displaced to lower temperatures, whereas it is displaced to higher temperatures, in reality. This contradiction is probably to be ascribed to not yet understood phenomena.*

TABLE 5.—TRANSFORMATION TEMPERATURES OF A 4.8 PER CENT NICKEL ALLOY AFTER HOLDING AT VARIOUS CONSTANT TEMPERATURES*

Holding temperature, °C.	Amount transformed, per cent	Transformation temperature, °C., on		
		Heating	Cooling	
			1st arrest	2d arrest
665	20	755	660	480
685	30	760	670	520
705	50	780	700	550
725	85	800	710	600

* Scheil.[540]

20. Scheil's Solubility Values for a 4.8 Per Cent Nickel Alloy.— During tests of alloys of various nickel contents (less than 30 per cent nickel) Scheil[540] found that alpha-gamma transformation could proceed, on holding at several constant temperatures, at temperatures somewhat lower than those found for ordinary rates of heating. The gamma-alpha transformation, however, could be induced at temperatures higher than the ordinary only in alloys containing less than 10 per cent nickel. Scheil interpreted this to mean that 10 per cent nickel is about the limit beyond which the atoms are "frozen in," because of the low temperature. Bischoff's[406] findings are in agreement; hence, it seems certain that alloys containing from 10 to 30+ per cent nickel are truly irreversible.

In alloys containing less than 10 per cent nickel, which transform at temperatures greater than about 500°C., change of nickel content by diffusion is possible, consequently equilibrium is possible. The assumed line *ab* in Fig. 8 is an approximate representation of the dilatation of the 4.8 per cent nickel alloy under

* If the change of nickel content upon isothermic transformation approaches the ideal course, the contradiction noted by Scheil is non-existent.

equilibrium conditions. The points a and b represent the temperatures of saturated alpha and gamma phases; they define one point each in the alpha and gamma boundary lines, as shown in Fig. 10.

21. X-ray Data on the Alpha-gamma Boundaries.—A few tentative data on the boundaries of the alpha-gamma region, given in Table 6, were obtained by Jette and Foote,[566] although it was found that the X-ray technique was not so suitable for solubility measurements on iron-nickel alloys as on many other alloys. It was concluded by these workers that complete investigation of the region must await construction of a high-temperature camera. High precision will be required, because the change of lattice constant is small.

22. Other Data on the Alpha-gamma Boundaries.—Investigations of the alpha-gamma boundaries of the iron-nickel diagram, by various methods, on alloys of varying degrees
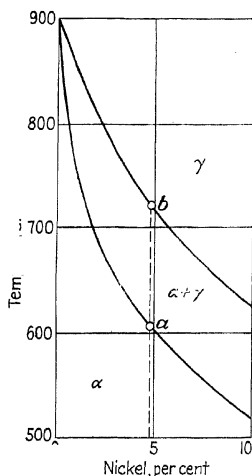
Fig. 10.—Equilibrium

TABLE 6.—X-RAY DATA ON THE BOUNDARIES OF THE ALPHA-GAMMA REGION
OF THE IRON-NICKEL DIAGRAM*

Nickel, atomic per cent	Annealing time, hr.	Annealing temperature, °C.	Phase limit	
			Phase	Nickel, atomic per cent
5.16	17	672	α	3.94
9.60	24	557	α	4.15
9.60	24	557	α	4.30
9.60	734	496	α	6.07
9.60	3150	456	α	5.91
24.81	457	585	γ	26.20
19.31	3150	456	γ	33.36
28.59	3150	456	γ	33.36

* Jette and Foote.[566]

of purity and manner of preparation, have yielded data too similar to warrant detailed examination of anything but the results. In brief, when collected, all fall within two bands, one obtained on heating and the other on cooling. This fact seems

Fig. 11.—The iron-nickel diagram.

to justify the diagram proposed by Merica,[572] shown in Fig. 11, who among others accepted irreversibility as unavoidable. Such a diagram is wholly satisfactory for practical purposes, since the transformations seem relatively insensitive to the preparation of the alloy, the rate of heating or cooling, and the method of detecting transformation.

Justification of this statement is to be found in Figs. 12 and 13, which summarize, for heating and for cooling, the data of Hanson and Hanson,[149] Kasé,[215] Peschard,[221] Honda and Miura,[256] Merz,[311] Scheil,[540] and Jette and Foote.[566] Excepting the points of Scheil and of Jette and Foote, it is to be seen that there
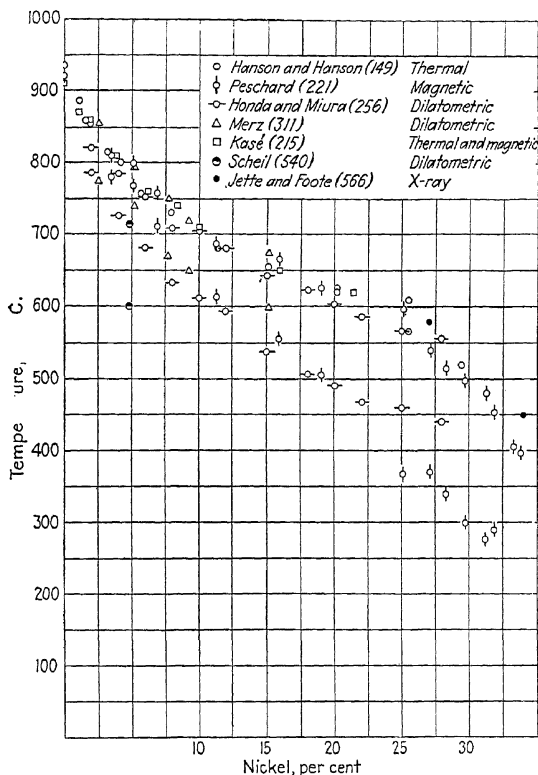
FIG. 12.—Boundaries of alpha and gamma phases on heating.

is little or no choice for any given composition. Scheil's points (obtained by holding at various constant temperatures) appear to be nearer those obtained by ordinary rates of cooling than of heating; if these points are accurate, the statement on page 33, that transformations upon heating ordinarily take place nearer the equilibrium temperature than those upon cooling, is contra-

dicted.   The data of Jette and Foote (X-ray determinations) are
of interest in that their points for the alpha-gamma boundary
agree with results ordinarily obtained upon cooling, whereas their
points for the gamma-alpha boundary agree with those ordinarily
obtained upon heating.   The meaning of these data is not clear.

○	Hanson and Hanson (149)	Thermal
◊	Peschard (221)	Magnetic
-○-	Honda and Miura (256)	Dilatometric
△	Merz (311)	Dilatometric
□	Kasé (215)	Thermal and magnetic
⊙	Scheil (540)	Dilatometric
•	Jette and Foote (566)	X-ray

FIG. 13.—Boundaries of alpha and gamma phases on cooling.

It is to be noted that the limit of existence of alpha phase
depends upon the temperature to which the alloys are cooled.
The limit for ordinary temperature is about 30 per cent nickel;
such an alloy could be carried through countless cycles of heating
and cooling without ever undergoing alpha ⇌ gamma trans-
formation.   The limit at −100°C., however, is about 34 per cent

nickel. According to Chevenard,[173] the limit at $-190°C$. is less than 34.5 per cent nickel, and data of Ribbeck[241] indicate that at absolute zero the limit is in the vicinity of 35 per cent nickel.

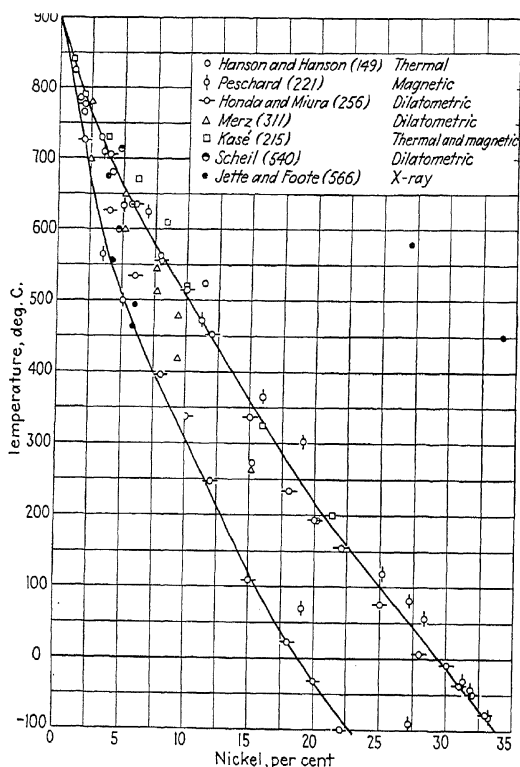Inasmuch as alloys near the limit of existence of alpha phase at low temperature must be far from the equilibrium condition, and since the boundaries of the alpha- and gamma-phase regions as determined by ordinary methods are in fair agreement, it seems possible only to follow the example of Merica and others by giving the boundaries found upon heating and upon cooling, as in Figs. 12 and 13.

23. Magnetic-inversion (Curie) Temperature.—Reversible iron-nickel alloys, existing in the concentration range from about
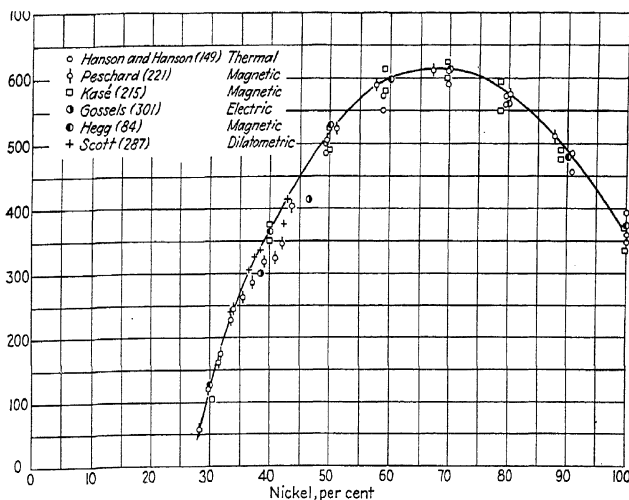
FIG. 14.—Magnetic-inversion temperatures of gamma-phase alloys.

30 to 100 per cent nickel at ordinary temperature, were so named when magnetic inversion (or Curie point) was considered to be a transformation in the sense that the alpha-gamma change is a transformation. The term "reversible" arose out of the fact that the change was found, for a given alloy, at or very near the same temperature despite direction of temperature change.

The first careful determination of magnetic-inversion temperatures of gamma-phase iron-nickel alloys was made by Hegg.[84]

Alloys (only nominal compositions were recorded) were made from electrolytic iron and shot nickel in an electric furnace. As the temperature of disappearance of ferromagnetism Hegg took the intersection with the temperature axis of the extrapolated curve of the square of magnetic moment per unit mass. These data and those of Hanson and Hanson[149] (thermal), Kasé[215] (magnetic), Peschard[221] (magnetic), Scott[287] (dilatometric), and Gossels[301] (resistivity) are summarized in Fig. 14. Although there is considerable scatter of points, there is no question about trend. If, however, only the points which should be most accurate (judged by internal evidence of the original report) are considered, as was done in drawing the curve shown in Fig. 14, the location of the magnetic-inversion line of gamma-phase alloys may be considered to be established satisfactorily. A qualitative explanation of the behavior of this line, based on ferromagnetic theory, was given recently by Mott.[618]

So far as magnetic inversion of alpha-phase alloys is concerned, there are no data which mean enough to record. It is certain that it is correctly represented schematically in Fig. 4, page 33, however.

24. Influence of Pressure on the Magnetic-inversion Temperature.—No change of magnetic-inversion temperature with pressure (up to 3500 metric atmospheres) of iron, nickel, or a 35 per cent nickel steel could be detected by Adams and Green.[370] (The foregoing materials, in the form of small transformer cores, were subjected to pressure in a water-jacketed bomb with internal electric heating.) The possibility of a slight reduction of inversion temperature at pressures greater than 3500 atmospheres was not excluded. (See also the mathematical treatment of Kornetzki.[532])

25. Microstructure of Iron-nickel Alloys.—Hanson and Hanson[149] examined the microstructure of iron-nickel alloys which had been annealed at 1300°C. and cooled in the furnace. The first effect noticed upon addition of nickel to iron was that the alloy was more difficult to etch. The grains appeared roughened with an irregular relief pattern, as is illustrated by Fig. 15 (6 per cent nickel). This may be compared with the ordinary ferritic structure of Fig. 16. Grain size is small at low nickel contents and increases with increased nickel content, although there is little change in microstructure of alloys containing from 10 to

25 per cent nickel. These alloys, illustrated by Figs. 17, 18, and 19, are of structure similar to that of martensitic carbon steel. Hanson and Hanson observed that the martensite-like structure was produced by cooling the alloys through their transformation temperatures and that it could not be suppressed, even by drastic
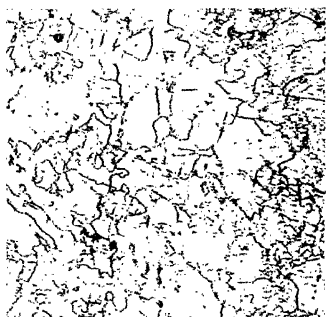
FIG. 15.—Structure of a 5.7 per cent nickel iron-nickel alloy annealed at 1300°C. and furnace cooled. 300×. (*Hanson and Hanson.*[149])

FIG. 16.—Ferritic structure of a 3.30 per cent nickel iron-nickel alloy, quenched at 700°C. after 48 hr. 300×. (*Hanson and Hanson.*[149])
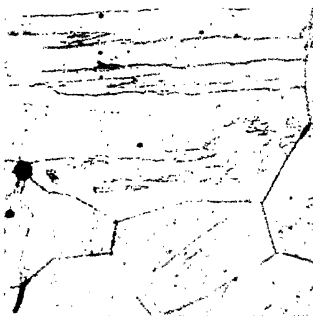
FIG. 17.—Structure of a 9.8 per cent nickel iron-nickel alloy, annealed at 1300°C. and furnace cooled. 300×. (*Hanson and* .

FIG. 18.—Structure of a 13 per cent nickel iron-nickel alloy, annealed at 1300°C. and furnace cooled. 300×. (*Hanson and Hanson.*[149])

quenching. The structure could be broken up only by cooling at very slow rate over certain ranges of temperature, or by long annealing at a suitable temperature.

Alloys containing more than 30 per cent nickel showed large-grained structures in which martensite-like markings were absent. The markings appeared in 30 and 40 per cent nickel alloys upon

cooling to −80°C. but did not appear in a 35 per cent nickel alloy treated similarly.

FIG. 19.—Structure of a 25.50 per cent nickel iron-nickel alloy, annealed at 1300°C. and furnace cooled.   150×. (*Hanson and Hanson.*[149])

Experiments were undertaken to determine the manner of decomposition of the martensite-like structure and the temperatures at which the decomposition would take place. Very slow rates of cooling and prolonged periods of annealing were utilized. Details are summarized in Table 7. From these data, the transformation curves of Fig. 20 were constructed. It is noteworthy that the upper boundary of the transformation region agrees closely with that determined by thermal analysis.
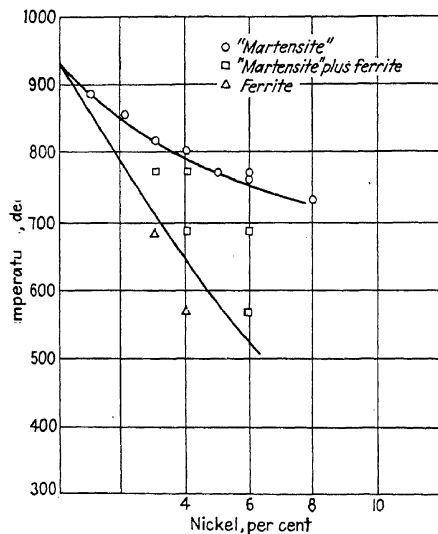
FIG. 20.—Transformation curves on cooling. (*Hanson and*

It is noteworthy also that thermal analysis did not detect the lower boundary.

TABLE 7.—MICROSTRUCTURE OF IRON-NICKEL ALLOYS AFTER VARIOUS
THERMAL TREATMENTS*

Nominal nickel content, per cent	Quenching temperature (preceded by annealing at 800°C.), °C.	Elapsed time, hr.	Structure
1	800	22	Ferrite
2	800	6	Martensite†
	700	48	Ferrite
3	800	22	Martensite
	700	48	Ferrite and martensite
	560	156	Ferrite
4	800	22	Martensite
	700	48	Martensite
	560	156	Ferrite, some martensite
	446	348	Ferrite
6	800	22	Martensite
	700	48	Martensite
	560	156	Ferrite and martensite
	446	348	Ferrite, some martensite
	370	700	Ferrite
8	700	48	Martensite
	446	348	Ferrite and martensite
	370	700	Ferrite and martensite
	324‡	288	Duplex, no martensite
9	324‡	288	Duplex, no martensite
11	324‡	288	Duplex, no martensite
13	324‡	288	Duplex, no martensite
15	700	48	Martensite
	560	156	Martensite
	446	348	Martensite
	370	700	Martensite
	345	964	Trace of duplex
	340	144	Duplex, no martensite
	324‡	288	Duplex, no martensite
25	560	156	Martensite
	446	348	Martensite
	370	700	Martensite
	345	964	Fine duplex, no martensite
	340	144	Fine duplex, no martensite
30	560	156	Homogeneous
	446	348	Homogeneous
	370	700	Homogeneous
	345	964	Homogeneous
	340	144	Duplex
35	446	348	Homogeneous
40	446	348	Homogeneous

* Hanson and Hanson.[149]
† So called by Hanson and Hanson.
‡ Slowly cooled from 1200°C.

Since even low rates of cooling of alloys containing more than 8 per cent nickel did not lead to transformation of austenite until a temperature of about 345°C. was reached, Hanson and Hanson concluded that the eutectoid line postulated by Osmond (see below) must exist between 350 and 340°C.   They concluded also that the temperature was confirmed by reheating experiments. The eutectoid concentration was estimated to be in the vicinity of 25 per cent nickel.
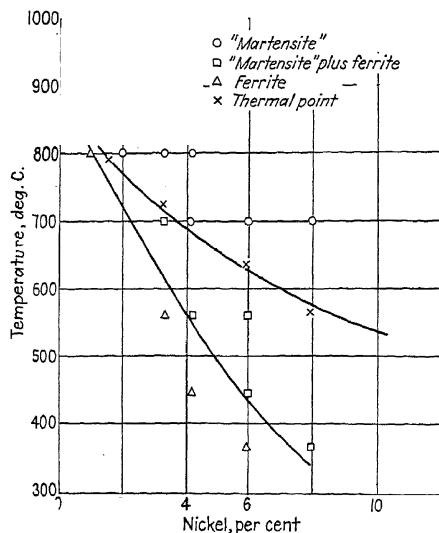
FIG. 21.—Transformation curves on heating.   (*Hanson and Hanson.*[149])

Boundaries of the transformation range on heating of the low-nickel alloys, as determined microscopically, are given in Fig. 21.

26. The Alleged Iron-nickel-alloy Eutectoid.—Study of the microstructure of meteoric iron led Osmond and Cartaud[58] to postulate a eutectoid transformation to explain the observed mixtures of alpha phase (called *kamacite*), gamma phase (called *taenite*), and the alpha-plus-gamma structure (called *plessite*). This is shown schematically in Fig. 22.   It is to be seen that this ingenious diagram is based upon the assumption that the magnetic inversion of high-nickel alloys represents a phase transformation (this assumption is now known to be false, of course).

Osmond and Cartaud's diagram was "confirmed" by several investigators and accepted by others; for example, by Benedicks[91] and by Smith[69] who fixed the eutectoid concentration at about 27 per cent nickel. Pfann[133] arrived at the value 17 to 18 per cent nickel for the eutectoid, 6 to 7 per cent for point *a* of Fig. 22, and about 27 per cent for point *b*. To Hanson and Hanson[149] it appeared "that the eutectoid line of Osmond's hypothetical diagram extends from 9 per cent to 30 per cent nickel approximately, and occurs at a temperature between 350 and 340°C."
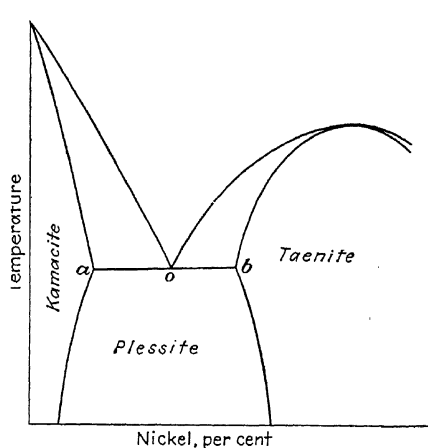
FIG. 22.—Schematic diagram illustrating the eutectoid postulated by Osmond and Cartaud[58] to account for structures found in meteoric iron.

27. Compounds of Iron and Nickel.—Because of discontinuity of properties of iron-nickel alloys, compounds, in the chemical sense, have been postulated frequently. Those reported most often have been Fe_2Ni (to account for low-expansion alloys of the invar type) and $FeNi_2$ (to account for the minimum of the liquidus and the maximum of the magnetic-inversion curve). In the light of present knowledge, however, none of these phenomena points to the presence of any compound. Other compounds reported are listed in Table 8.

It is to be inferred from the region of the liquidus of the iron-nickel diagram that no compound exists at those temperatures. Data on the low-temperature portion are perhaps less conclusive,

but here also there is no direct evidence of any compound. On the contrary, the large positive deviation of the specific-volume curve from rule-of-mixtures values (page 120) indicates that the tendency is opposite to that of compound formation.

TABLE 8.—REPORTED COMPOUNDS OF IRON AND NICKEL*

Compound	Nickel, per cent	Reference
Fe₇Ni	13.05	Arnold and Read[108]
Fe₂Ni	25.92	Ruer[79]
Fe₂Ni	34.39	Ruer[79] Burgess and Aston[81] Chevenard[110,231] Portevin and Chevenard[168] Chevenard and Portevin[212] Peschard[221] Schulze[266]
Fe₃Ni₂	41.19	Peschard[221]
FeNi₂	67.78	Osmond[34] Ruer and Schüz[87] Chevenard[110] Smith[169] Peschard[221]
		Broniewski and Smolinski[443]
FeNi₃	75.94	

* The reference list is incomplete.

The behavior of certain properties of these alloys has not yet been analyzed satisfactorily, consequently the issue is not closed entirely. However, on the basis of present knowledge of intermetallic compounds, evidence is heavy against the existence of any in iron-nickel alloys.

C. AUTHOR'S SUMMARY

1. Since only three phases—alpha (delta), gamma, and the melt—exist in the iron-nickel system, and since the degree of intersolubility of iron and nickel is high, the diagram is simple.

That shown by Fig. 23 was arrived at by selection and interpolation of the available data.
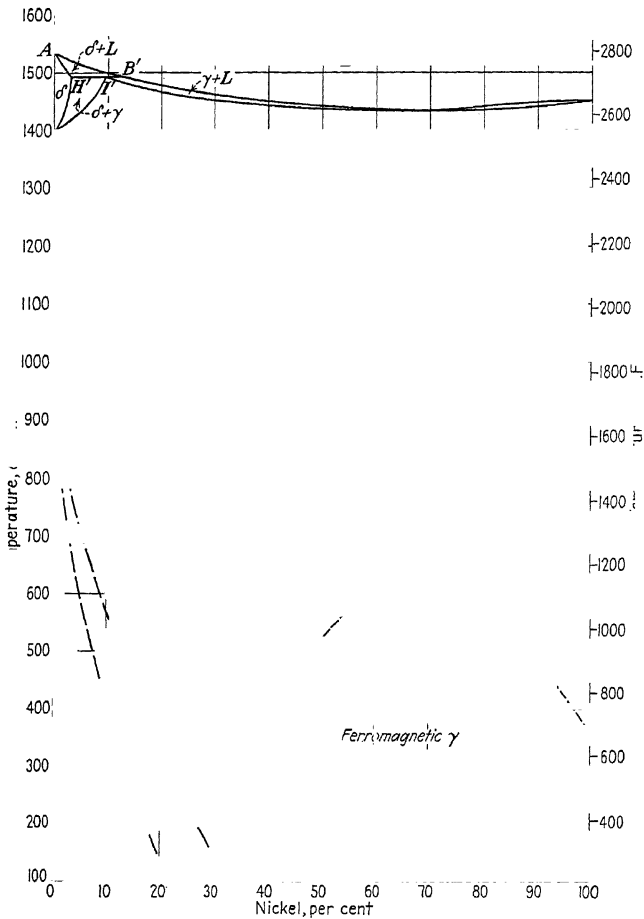

FIG. 23.—The selected iron-nickel diagram.

2. There is some uncertainty attached to the boundaries of the peritectic region, but scarcely enough to be of more than academic interest. The peritectic temperature selected (1494°C.) is perhaps somewhat low and the concentrations corresponding to

points H', I', and B' are subject to revision. The remainder of the liquidus-solidus portion of the diagram is likewise subject to revision, although it is considerably better established than corresponding portions of some other diagrams. On the whole, the melt-solid boundaries may be considered to be established satisfactorily for all purposes, possibly excepting the most exacting, such as certain types of thermodynamic treatment.

3. Moving to the low-temperature portion of Fig. 23, it is to be seen that the alpha-gamma boundaries have been indicated by broken lines. This is to remind that, even in the range in which equilibrium is seemingly possible, there are no conclusive data which would permit location of the equilibrium boundaries with any useful degree of certainty. From the practical point of view, equilibrium boundaries in this instance would be of little if any value. The required information is given by Figs. 12 and 13, pages 43 and 44, which show the boundaries observed with ordinary rates of heating and cooling.

4. It is the consensus of modern investigators of the phenomenon of irreversibility that iron-nickel alloys "freeze in" at about 500°C. upon cooling. This means that at all temperatures below 500°C., atomic diffusion either ceases or becomes negligibly small, consequently that equilibrium is either impossible or extremely difficult to attain. The concentration range of alloys in which alpha-gamma equilibrium is possible is therefore limited, since the phase boundaries decline in temperature with increasing nickel content. One investigator (Scheil, page 40) concluded that the limit is about 10 per cent nickel. There seems no doubt that this value is reasonable, although subsequent work may shift it somewhat in either direction. It is probably desirable also to keep in view Jette and Foote's (page 41) inconclusive but possibly accurate indication that the spread between the alpha and gamma boundaries is much greater than hitherto supposed. Even so, it is certain that there exists a temperature range over which the alloys are truly irreversible.

5. The magnetic-inversion curve given in Fig. 23 was selected from data obtained by magnetic, thermal, electric-resistivity, and dilatometric methods. It is true that magnetic-inversion temperature is largely a matter of definition (as has been emphasized repeatedly in recent years), but the greatest indication of discontinuity obtained by the several ordinary methods occurs

at a constant temperature—or nearly so—for a given alloy, consequently the curve represents such points. It is also true that a magnetic inversion does not mean a phase change in the Gibbsian sense, but it is the custom to indicate the hazy division between ferromagnetic and paramagnetic phases. The custom is unusually useful for the iron-nickel diagram, because the magnetic properties of the alloys are especially important.

6. Only one microstructural constituent is worth mention here and that is the martensite-like product which results from gamma-to-alpha transformation at low temperature. This constituent differs from martensite in that its structure is cubic (rather than tetragonal); the microstructural similarity arises from the fact that its mechanism of precipitation is similar.

7. So far as the microstructure of meteoric iron is concerned, it is sufficient to state that all is satisfactorily accounted for by alpha-gamma boundaries as shown in Fig. 23. There is no need to postulate an iron-nickel eutectoid as was done—reasonably enough—by early metallographers.

8. Discontinuities, or maxima, or minima of many properties which appear when plotted against composition led many of their observers to postulate compounds of iron and nickel. One favorite was Fe_2Ni (to explain invar); another was $FeNi_2$ (to account for the minimum of the liquidus and the maximum of the magnetic-inversion curve at about 68 per cent nickel). The weight of the evidence, however, is against the existence of any compound whatever. Furthermore, current interpretations of the aforementioned discontinuities, maxima, and minima do not require compounds.

9. The major gap in knowledge of the iron-nickel diagram seems to center about the alpha- and gamma-phase boundaries. It is suggested that much could be learned by the use of a dilatometer capable of being maintained at selected temperatures for long periods of time. Such technique is sure to be more usual in the future. Another method of investigation would use a high-temperature X-ray camera capable of high-precision measurement, but inherent difficulties of this method are greater than those of the dilatometric method—or at least they seem so at present.

CHAPTER III

THE IRON-CARBON-NICKEL DIAGRAM

Relevant Data—The Diagram—Author's Summary

The iron-carbon-nickel diagram, among the important ferrous ternaries, has received an extraordinary amount of inattention. The single diagram in existence was reported as long ago as 1925, and, in common with most ternary diagrams for metallic systems of that time, it is rather primitive.

The problem is difficult. The already thermodynamically unstable iron carbide is even less stable when it contains nickel; *i.e.*, nickel is a "graphitizing" element. This leads to experimental and to interpretative troubles. Furthermore, in certain ranges of concentration and temperature, the velocity of transformation is so low that establishment of equilibrium in any reasonable time is either difficult or impossible. Finally, there is the difficulty arising from uncertainties attached to the contiguous binary diagrams.

So far as technology is concerned, concentrations of useful alloys lie in a relatively small portion of the concentration triangle. Alloys containing the most carbon—cast irons—contain a maximum of 40 to 45 per cent nickel, and usually less. Nickel steels seldom contain more than 0.75 per cent carbon, excepting the case of case-hardened steels. If such alloys were ever in the equilibrium condition, the quantitative phase diagram would be useful as a means of determining transformation temperatures. That the equilibrium phase boundaries are not known quantitatively is no great drawback: commercial steels and cast irons are seldom, if ever, in the equilibrium condition. Even a qualitatively correct phase diagram, however, can be useful by showing the number and nature of participating phases, and this is nearly all that can be expected from any iron-carbon-nickel diagram which can be constructed from available data.

A. RELEVANT DATA

Before attempting to construct an iron-carbon-nickel diagram capable of accounting reasonably for the behavior of iron-carbon-nickel alloys—nickel steels and cast irons—the few published data will be examined.
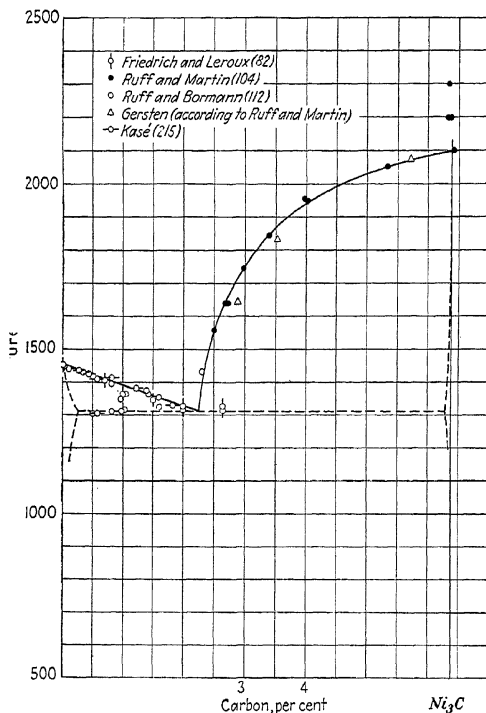
FIG. 24.—The nickel-carbon diagram.

28. Contiguous Binary Diagrams.—None of the three contiguous binary diagrams—iron-carbon, iron-nickel, and nickel-carbon—of the ternary diagram is free of doubt. The status of the iron-nickel diagram was given in the preceding chapter; uncertainty is attached mainly to the alpha- and gamma-phase boundaries.

There is fair agreement among iron-carbon diagrams published within recent years (see, for example, preceding monographs

of this series and the metallurgical handbooks), but this agreement is illusory, especially in the manner of representing the region of existence of iron carbide. However, in the present inadequate state of knowledge it is possible to proceed only from one of these representative diagrams. Study of the problem can be based on Volume I of "The Alloys of Iron and Carbon."

Available data on the nickel-carbon diagram are summarized in Fig. 24. Except those of Friedrich and Leroux[82] and of Kasé[215] all were obtained in the laboratory of Ruff.[104,112]

Examination of the evidence indicates that the carbide Ni_3C exists in the melt and that this carbide tends to decompose upon separation from the melt. It is clear, however, that the diagram is of the eutectic type (coordinates of the eutectic are approximately 2.25 per cent carbon and 1310°C.) and that the high-temperature portion is known with fair certainty. There is little information, on the other hand, on the low-temperature portion; i.e., the solubility of nickel in Ni_3C and the solubility of carbon in nickel. From an X-ray study of Ni_3C, however, Jacobson and Westgren[452] concluded that the solubility of nickel in Ni_3C is very small.

In passing, it may be added that Jacobson and Westgren prepared their Ni_3C by carburizing nickel powder in an atmosphere of carbon monoxide for 24 to 168 hr. at a temperature of 270 to 300°C. The crystal structure was found to be hexagonal close packed with $a = 2.646$ Å. and $c = 1.636$ Å. Hence, Ni_3C cannot, in the solid state, be completely intersoluble with iron, Fe_3C, or nickel. This statement ignores the very improbable possibility that there is a continuous transition from the orthorhombic Fe_3C to the hexagonal close-packed Ni_3C.

29. Kasé's Iron-carbon-nickel Diagram.—The only investigation of iron-carbon-nickel alloys conducted with the intention of determining the diagram was that of Kasé.[215] This consisted of thermal, microscopic, and magnetic analyses of 126 alloys made from nickel shot, ingot iron, and "white pig iron"; the alloys, therefore, cannot be considered to have been very pure. (Owing to certain intrinsic difficulties, no effort is made to establish the degree of purity.) From these data, however, Kasé constructed the ternary diagram, shown in perspective in Fig. 25, and described it substantially as follows:

In Fig. 25, $ABB'A'$, $AA'D'D$, and $BB'C'C$ represent the planes containing the binary diagrams iron-nickel, iron-carbon, and nickel-carbon respectively. $ABFE$ and $ABGH$ are respectively the liquidus and solidus surface of austenite (neglecting the
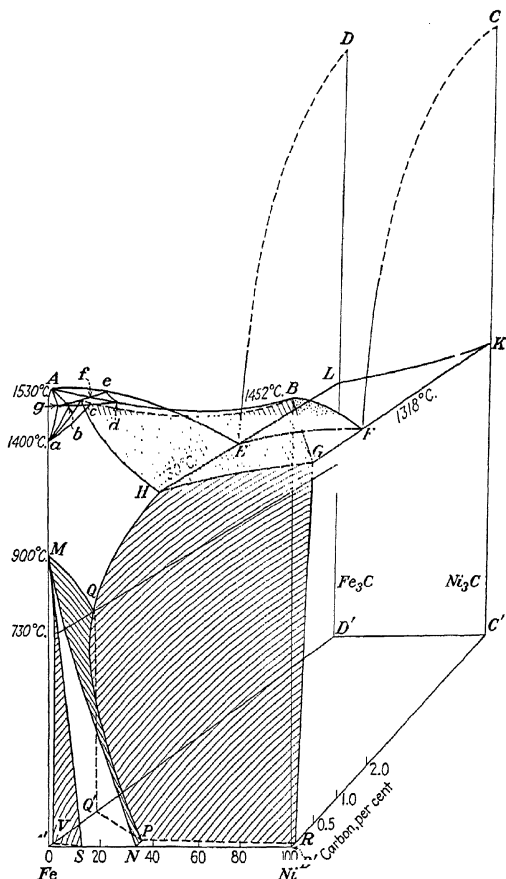

Fig. 25.—Kasé's[215] iron-carbon-nickel diagram.

small delta-phase space). $CDEF$ is the liquidus surface of the solid solution of cementite and nickel carbide.

Curve EF, whose terminal in the nickel-carbon plane lies at 1318°C. and in the iron-carbon plane at 1130°C., is the eutectic

line of the ternary system.   *GFKLEH* is the surface of beginning of eutectic crystallization.   The surface of ending of eutectic crystallization (not shown) is generated by a series of horizontal lines connecting curves *GH* and *KL*.   In the space *ABGHEF*, austenite and the melt coexist; in the space *CDEFKL*, carbide and the melt coexist.

Surface *GHQPR* is the solubility surface of carbide or carbon in austenite.   *MQPN* is the solubility surface of ferrite in austenite; hence, the intersection *QP* of these surfaces is the eutectoid line.   Space *MSVA′* represents solid solution of iron, carbon, and nickel.   *MV* is the solubility curve of carbon in iron; *MS* is the solubility curve of nickel in iron. The remainder of the description is concerned with the peritectic region.

30. Criticism of Kasé's Diagram.—Inspection of Fig. 25 discloses that it contains certain violations of the phase rule, as was noted by Schottky and Stäblein;[245] for example: the eutectoid portion of the diagram.   (The divergence from a permissible construction may be observed by comparison with Fig. 33, page 67.)   There is no need, however, of piecemeal examination. It will suffice to observe that Kasé's assumption of complete intersolubility of iron carbide and nickel carbide is not in agreement with experimental fact (page 64), although it must be stated that this was not known in 1925.   The important point is that a large portion of Kasé's diagram is therefore necessarily invalid.

31. Other High-temperature Data.—A few data on the peritectic region of some industrial steels were supplied by Andrew and Binnie.[290]   The samples included nickel, nickel-chromium, nickel-chromium-vanadium, and nickel-chromium-molybdenum steels.   Because of the small number of samples and the variety of analyses, the data are of little value singly, but together they show small departure from peritectic-region temperatures of the iron-carbon diagram.   This finding is in agreement with the underlying principles.

Since the data of Andrew and Binnie are not suitable for construction of the ternary diagram, they are not reproduced. It seems sufficient to report a result of perhaps practical interest: the "melting point" of low-alloy steels is lowered roughly 5°C. for each 1 per cent nickel-plus-chromium.

Schichtel and Piwowarsky[321] reported data on the line of twofold saturation originating in the iron-carbon eutectic.   These data are utilized in the following section.

32. Examination of Iron-carbon-nickel Data.—The thermal data of Kasé[215] were examined by replotting in the form of
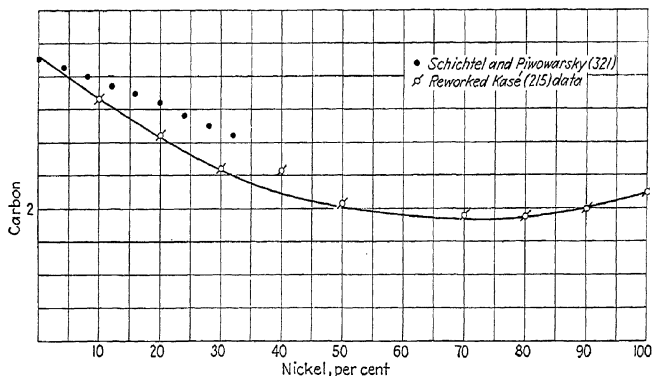
FIG. 26.—Basal projection of line of twofold saturation in melt.
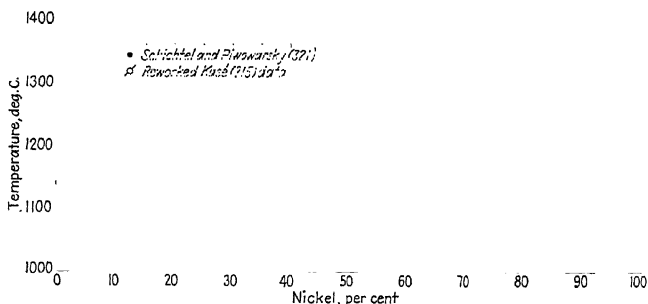
FIG. 27.—Same line as shown in Fig. 26, projected on the iron-nickel plane.

constant-nickel sections.   By means of smooth curves drawn through—or near—the more or less scattered points, estimate was made of temperature and carbon concentration of the "eutectic" point for each section.   These points are shown in Figs. 26 and 27, together with those of Schichtel and Piwowarsky.[321]   By means of these curves, the original liquidus sections were adjusted to form a self-consistent group.

No attempt was made to reconcile the two sets of data, because both agree in trend and neither is necessarily trustworthy. Merely for the reason that Kasé's data cover a wider range of concentration, they were used as adjusted for self-consistency.
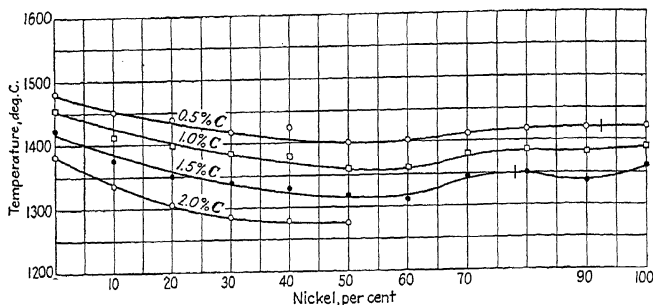
FIG. 28.—Constant-carbon-content sections of the iron-carbon-nickel diagram.

The next step was to construct as many constant-carbon-content sections as possible, in units of 0.5 per cent carbon; these are shown in Fig. 28. From these sections, the isothermic sections shown in Fig. 29 were constructed; they seem to rule out the existence of a line of doubly saturated melt originating in
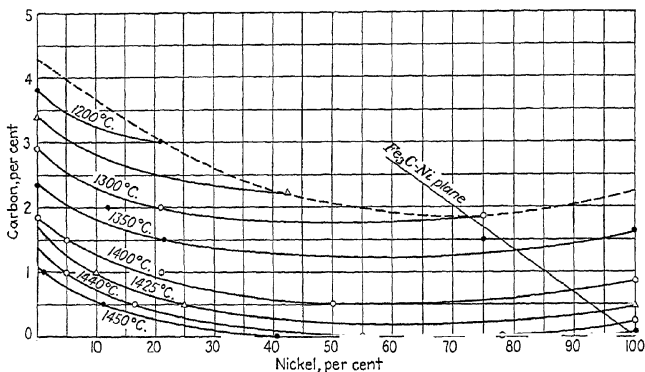
FIG. 29.—Isothermic sections of the iron-carbon-nickel diagram.

the iron-nickel plane, and consequently to exclude possible diagram V, page 74.

Intersections of plane Fe$_3$C-Ni with the sections of the liquidus surface are indicated by short vertical lines in Fig. 28. The

required discontinuity seems to be indicated, but the evidence is slender. This is likewise true of Fig. 27.

Seemingly the most to be derived from examination of available data on the high-temperature portion of the diagram is some knowledge of the trend of the line of twofold saturation of the melt. This knowledge is not worthy of much confidence.

B. THE DIAGRAM

Scarcity of data and unsolved problems, such as the behavior of the carbide or carbides, make impossible construction of the diagram- from experimental work alone. It is often possible, guided by theory, to construct a diagram which is consistent with the few experimental observations, but there are so many open questions on the iron-carbon-nickel system that the procedure is less satisfactory than usual. Some possible diagrams are useful only in that they illustrate the more improbable constructions. That the iron-carbon-nickel diagram is no nearer solution than it is may be ascribed mainly to deficiency of knowledge of the iron-carbon system.

33. Possible Phases of the Iron-carbon-nickel System.—Suggested designations of possible phases of the iron-carbon-nickel system are

1. α (a solid solution of iron, nickel, and carbon).
2. γ (a solid solution of iron, nickel, and carbon).
3. Ca (nominally iron carbide, Fe_3C).
4. H (nominally nickel carbide, Ni_3C).
5. G (graphite).
6. L (the melt).

Since there is no evidence that graphite can coexist in equilibrium with either or both of the carbides, it is permissible to assume temporarily that carbon is always precipitated as carbide—at least over the lower range of carbon content—hence, that the system behaves along its solubility curves and surfaces as if graphite does not participate. (Although inaccurate, strictly speaking, no confusion can result from speaking of such geometric properties of the system.) The number of phases to consider is thus reduced to five.

The surest way of determining the proper combinations of existing phases of a ternary system is by considering the three-phase equilibria.

Observed three-phase equilibria are:

1. $\alpha + \gamma + L$.
2. $\gamma + L + Ca$.
3. $\gamma + L + H$.

The first equilibrium, $\alpha + \gamma + L$, is the peritectic; it consequently is eliminated from further consideration, because it cannot influence the remainder of the diagram. The second,
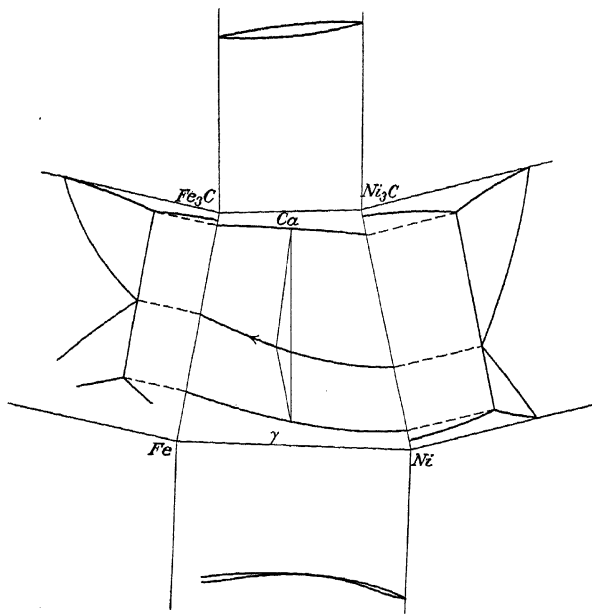
Fig. 30.—Schematic possible diagram I.

$\gamma + L + Ca$, originates from the eutectic of the iron-carbon system. The third, $\gamma + L + H$, originates from the eutectic of the nickel-carbon system.

Possibility I.—If carbide phases Ca and H were completely intersoluble, the type of diagram devised by Kasé (page 59) might follow. This is shown schematically in Fig. 30. This possibility is ruled out by the fact that the two carbides are not completely intersoluble.

Possibility II.—Since the two carbides are not intersoluble, the more reasonable expectation would be that the possible

quasi-binary section is of the eutectic type. This leads to the ternary-eutectic type of diagram, shown schematically in Fig. 31. But one reason of several is sufficient to rule out this possibility; the line of twofold saturation whose terminal is the iron-carbon eutectic is shown to increase in temperature as it progresses into the ternary space by the data of Kasé[215] and of Schichtel and Piwowarsky,[321] summarized in Fig. 27.
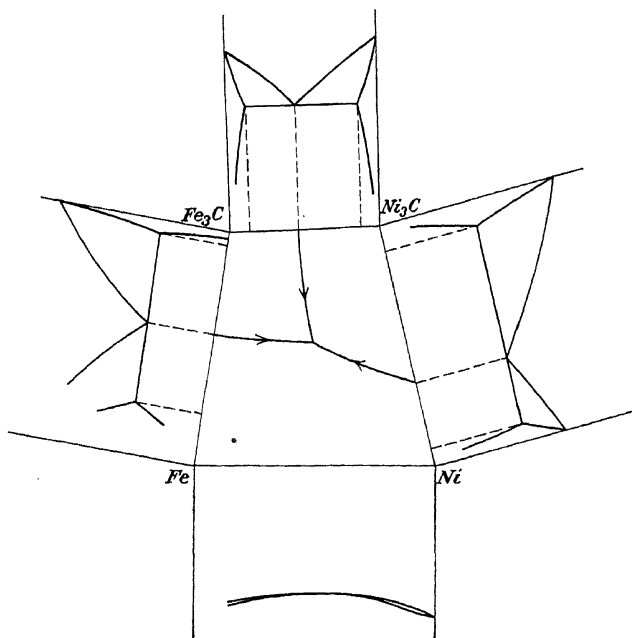
FIG. 31.—Schematic possible diagram II.

Possibility III.—The slope of the line of twofold saturation discussed in the foregoing paragraph could be accounted for if there existed the transition-plane type of four-phase equilibrium. This would demand that a possible quasi-binary section Fe_3C-Ni_3C is of the peritectic type—which is doubtful. It is also possible that the $Ca + H + L$ equilibrium changes from the eutectic to the peritectic type in the ternary space, but this is even more doubtful.

Possibility IV.—If there exists a quasi-binary section Fe_3C-Ni, then there exists a partial ternary system Fe-Fe_3C-Ni, from which Ni_3C is excluded. One of the several variants will now be the subject of detailed discussion, for the reason that it is capable of plausible interpretation of nickel steels. This should not be
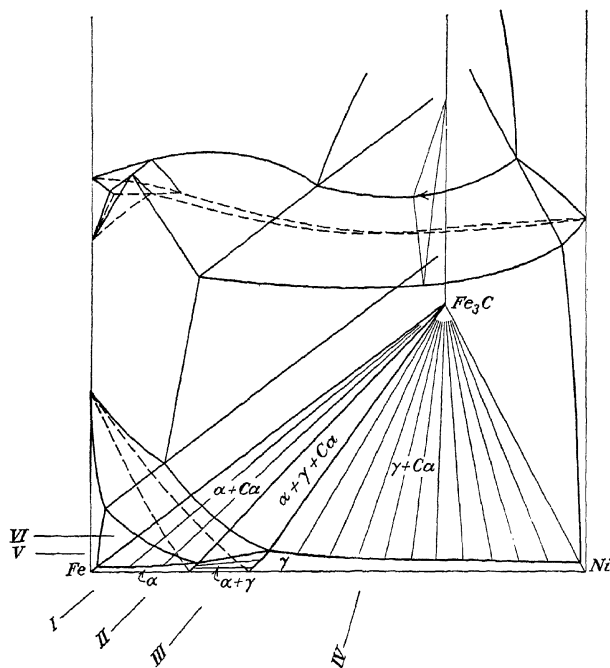
FIG. 32.—Perspective view of possible diagram IV.

interpreted to mean, however, that the correct partial system—if such exists—has been found.

34. A Schematic Iron-carbon-nickel Diagram. *Possibility* IV. For the purpose of learning the appearance of sections of this possible partial iron-carbon-nickel diagram, some have been constructed on the assumption that section Fe_3C-Ni is quasi-binary. It has been assumed also that this section is of the eutectic type. The resultant diagram is shown in perspective in Fig. 32.

The manner of dealing with the carbide phase, as stated before, is problematic. It is assumed here, however, that Fe_3C (probably containing some nickel) is precipitated as such—at least over certain ranges of concentration—and that graphite appears as a decomposition product. Positions of phase boundaries, especially at lower temperatures, are therefore uncertain,
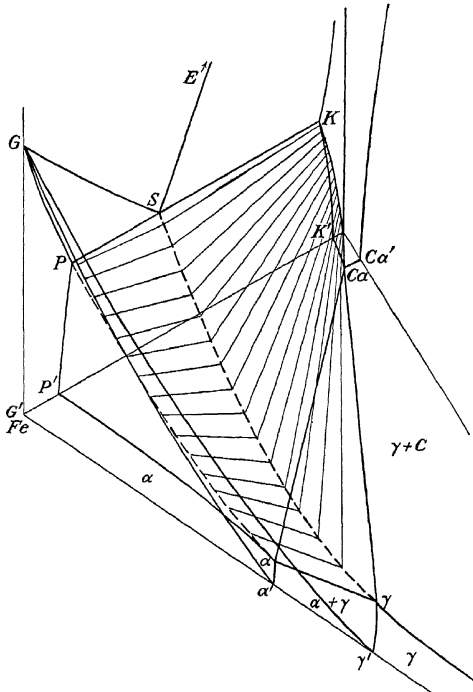
FIG. 33.—Schematic representation of the eutectoid region.

but the diagram at least is capable of interpretation of nickel steels in accordance with the phase rule.

Because of the uncertainty of thermal behavior of Fe_3C, the Fe_3C corner of the prism is uncompleted—mainly to remind that uncertainty exists—or, if it is preferred, as an admission of ignorance.

Of greatest practical interest, perhaps, is the "eutectoid" region. This is shown schematically in Fig. 33. The eutectoid

horizontal *PSK* of the iron-carbon diagram in the ternary space is expanded and any isothermic section of the alpha-plus-gamma-plus-carbide region is triangular. The limit is the triangle $\alpha + \gamma + Ca$ which lies in the base of Fig. 33. This arises from the fact that the three-phase region is bounded by three ruled surfaces which are generated by an infinite number of isothermic straight lines connecting saturation curves $P\alpha$ and $S\gamma$, $P\alpha$ and KCa, and $S\gamma$ and KCa.
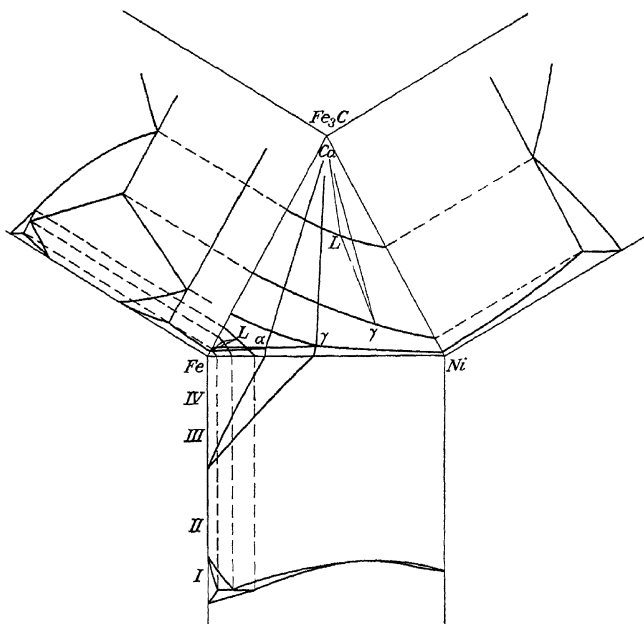
FIG. 34.—Schematic possible diagram IV.

The shapes of the surrounding regions may be determined by inspection of Figs. 32 and 33, or perhaps more easily by inference from plane sections. To facilitate construction of such sections, Fig. 34 is given. In the triangular portion of this diagram, the lines of twofold saturation have been projected upon the base of the prism. Positions of isothermic sections are indicated by Roman numerals.

35. Isothermic Sections of Fig. 34.—Isothermic section I, Fig. 35, corresponds to a temperature between that of peritectic

transformation and of the upper alpha $\rightleftharpoons$ gamma transformation
of iron. Thus, from left to right, the fields to appear successively
are: 1, alpha; 2, alpha plus gamma; 3, gamma; 4, gamma plus
melt; 5, melt; and 6, melt plus carbide.
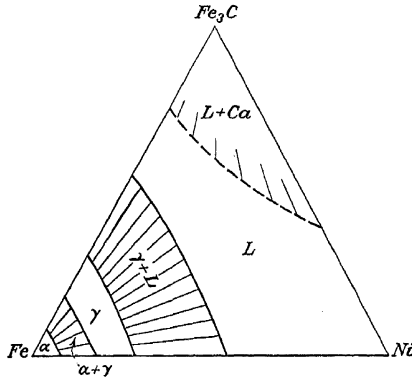
FIG. 35.—Isothermic section I of Fig. 34.

Section II, Fig. 36, lies below the eutectic temperature of the
Ni-Fe$_3$C diagram but above that of the Fe-Fe$_3$C diagram.
Since the three-phase gamma-melt-carbide region is intersected,
its section appears in triangular form. To be noted also are the
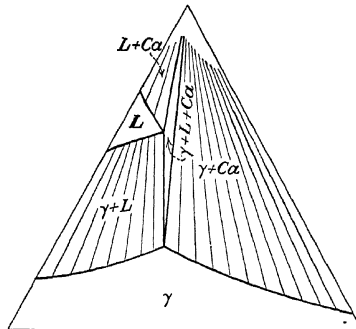
FIG. 36.—Isothermic section II of Fig. 34.

increased area of the gamma field and the decreased area of the
melt field as compared with Fig. 35.

Section III, Fig. 37, lies below the temperature of the lower
alpha $\rightleftharpoons$ gamma transformation but above that of the iron-

carbon eutectoid. Thus, alpha and alpha-plus-gamma fields appear as well as gamma and gamma-plus-carbide fields. Fields containing the melt do not appear.
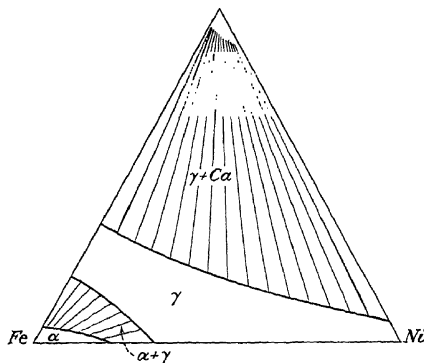
Fig. 37.—Isothermic section III of Fig. 34.

Section IV, Fig. 38, corresponds to a temperature below that of the iron-carbon eutectoid. This section shows that gamma phase ("austenite") exists, even at room temperature, over certain ranges of concentration. In the equilibrium condition,
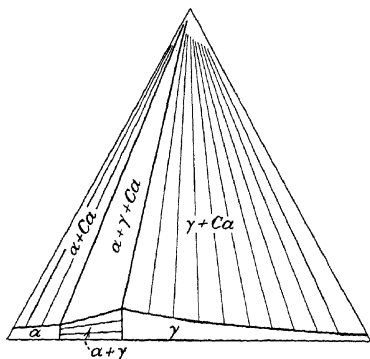
Fig. 38.—Isothermic section IV of Fig. 34.

iron carbide cannot exist at the temperature represented by this section. Graphite is therefore to be expected in all alloys in which equilibrium is approached. Practically speaking, the decomposition of the carbide becomes easier as the nickel

content becomes greater and, consequently, graphite appears without special treatment in the higher nickel iron-carbon-nickel alloys. It follows that Fig. 38, which shows carbide phase, is
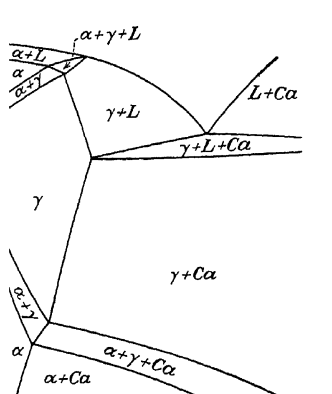
FIG. 39.—Vertical section I of Fig. 34 (position is shown in Fig. 32).

not strictly accurate. However, this section seems to give a workable picture of the constitution of alloys of present importance.
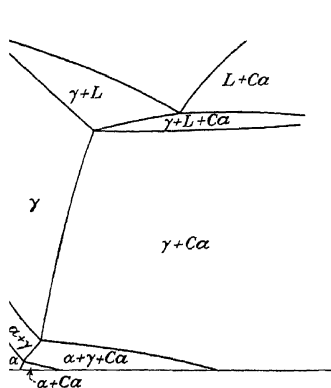
FIG. 40.—Vertical section II of Fig. 34 (position is shown in Fig. 32).

36. Vertical Sections.—Positions of vertical sections of the schematic iron-carbon-nickel diagram are indicated in Fig. 32 by Roman numerals. Each of the first four sections represents a

constant ratio of nickel to iron.   The first, section I, Fig. 39,
represents a ratio of approximately 5 nickel to 95 iron.   Its
similarity to the iron-carbon diagram is apparent, the differences
being mainly the expansion of three-phase regions to areas and
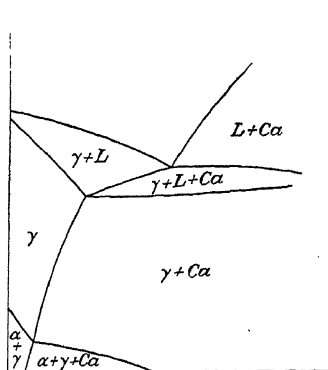
Fig. 41.—Vertical section III of Fig. 34 (position is shown in Fig. 32).

the intersection of the alpha-plus-gamma-plus-carbide region
with the base of the section.   This section is characteristic of
all which include the ordinary nickel steels; only the areas
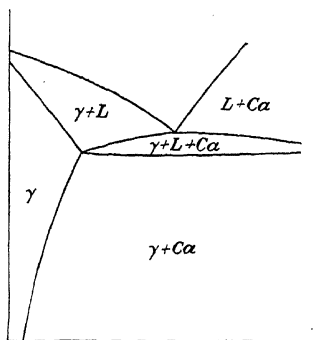
Fig. 42.—Vertical section IV of Fig. 34 (position is shown in Fig. 32).

of the fields change from section to section.   Section II, Fig.
40, is similar, except that the peritectic region no longer appears;
the nickel-iron ratio is approximately 15 to 85.   The extension
of the gamma field to still lower temperatures is to be noted.

Section III, Fig. 41, representing a ratio of approximately 20 to 80, passes through the alpha-plus-gamma region at once; consequently, no alloy consisting wholly of alpha phase is possible.
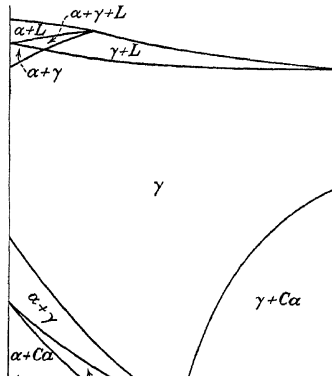
Fig. 43.—Vertical section V of Fig. 34 (position is shown in Fig. 32).

Section IV, Fig. 42, is characteristic of all ratios of nickel to iron greater than about 30 to 70.   These sections are so simple as to require no comment.
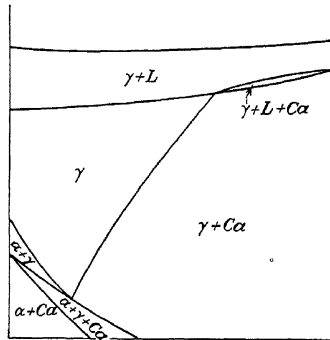
Fig. 44.—Vertical section VI of Fig. 34 (position is shown in Fig. 32).

The remaining sections indicated on Fig. 32 are for constant carbon content.   These are Figs. 43 and 44 and are self-explanatory.

The only data of consequence on alpha-gamma boundaries of iron-carbon-nickel alloys were obtained by Bain.[405] The alloys contained about 0.55 per cent carbon, up to 3.9 per cent nickel, and several tenths of 1 per cent each of manganese and silicon. The actual experimental results* were used for the construction of Fig. 45. Except for the difference of curvature, the boundaries shown agree with those given in the lower left portion of Fig. 44.

37. Possibility V.—Because a minimum exists in the liquidus of the iron-nickel diagram, it is possible that, assuming further
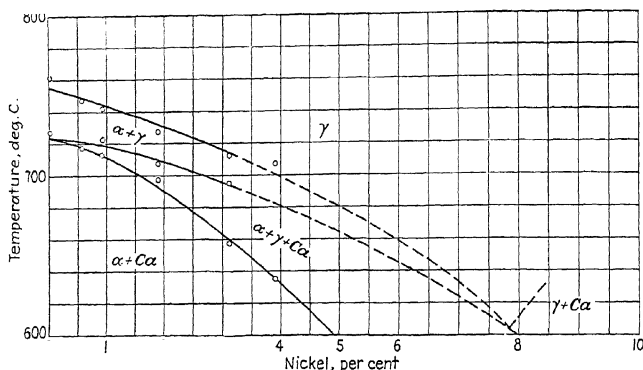
FIG. 45.—Vertical section at 0.55 per cent carbon. (*Bain, private communication.*)

diminished intersolubility in the ternary space, there exists a range over which the melt is doubly saturated with iron and nickel; *i.e.*, there exists a range of eutectic-type equilibria. This results in a diagram shown schematically in perspective in Fig. 46, in which four-phase equilibrium of the transition-plane type exists. The transition plane is shown projected upon the base of the prism in Fig. 47.

The construction of Fig. 46 demands that two gamma phases, differing in composition, may coexist over certain ranges. They are denoted γ_1 (which may be considered to be γ_{Fe}) and γ_2 (which may be considered to be γ_{Ni}). This possibility does not seem probable.

* Private communication.

The foregoing constructions have been based on the orthodox iron-carbon diagram. Before summarizing them, it may be useful to indicate a somewhat different approach.

38. An Iron-carbon Diagram.—The problem of the iron-carbon diagram, as stated earlier, has never been solved entirely. The fragmentary evidence to date leads to the conclusion that free
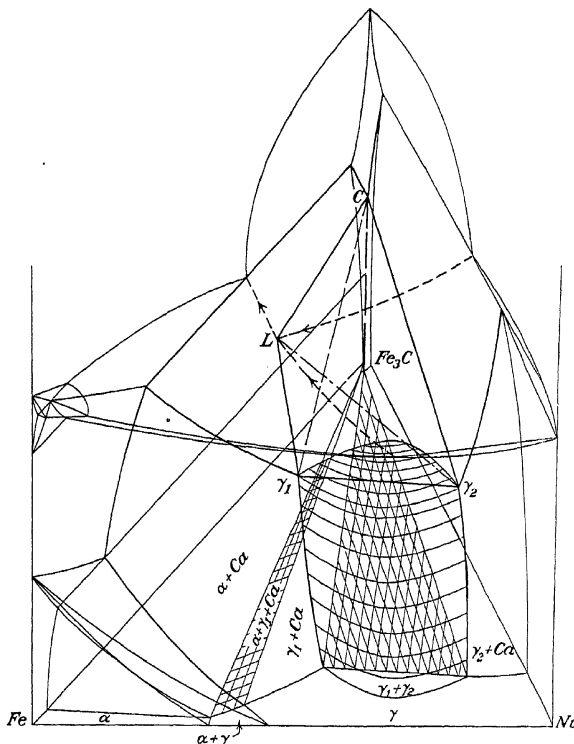
FIG. 46.—Perspective view of possible diagram V.

iron carbide (Fe_3C) is unstable at all temperatures. However, the carbide seems to persist in solution, as in the gamma phase and in the melt. Furthermore, the carbide seems to be precipitated from such solutions—at least from those rich in iron. This fact, as suggested by Epstein,[560] may be an example of operation of Smits's rule that "if the modifications of an allotropic

substance differ widely, as regards their compositions, from a liquid which is supercooled with respect to the different modifications, that modification will, as a rule, first spontaneously separate out the composition of which most nearly approximates to the composition of the liquid." The theoretical foundation, if any, of this empiric rule is unknown.

According to Scheil,[244] iron carbide becomes stable at higher pressures, but the pressure-temperature-concentration diagram given by him is too speculative to be reliable.
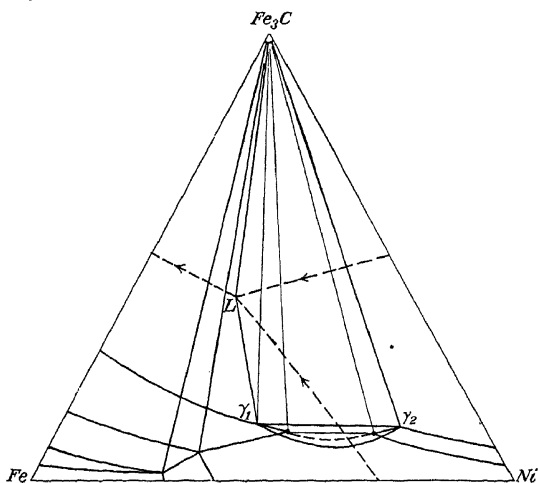
Fig. 47.—Basal projection of the transition plane of Fig. 46.

A possible solution of the problem is indicated by Fig. 48, which is based mainly on the solubility data of Ruer and Biren.[155] These data are interpreted to mean that, upon cooling, iron carbide appears—when it does appear—as a product of peritectic transformation. The diagram is completed to show the vapor phase. Thus, Fig. 48 is largely hypothetical; it is assumed to account for behavior over those ranges of concentration and temperature in which iron carbide participates in the various equilibria. In those ranges in which iron carbide does not participate, the diagram is simplified by omission of the aforementioned peritectic transformation. In this case, of course, the eutectic and eutectoid horizontals are extended to the iron-in-carbon solubility line.

The question of whether iron carbide appears as a product of peritectic transformation is more important than it may seem
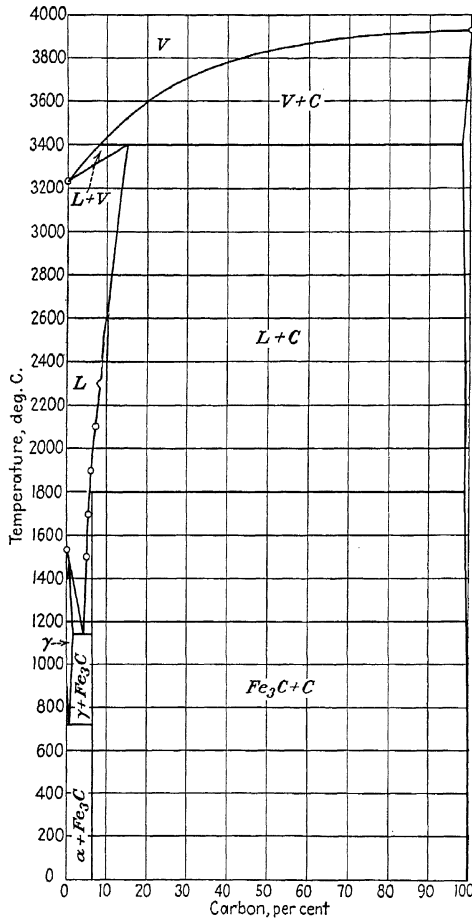
FIG. 48.—A possible iron-carbon diagram.

because, if the peritectic transformation exists, then quasi-binary sections of the iron-carbon-nickel diagram are impossible.

The recent paper by Wells[619] which describes graphitization in high-purity iron-carbon alloys containing as little as 0.13 per

cent carbon shows that the problem of the iron-carbon diagram is far from solved.

39. Iron-carbon-nickel Diagrams Based on Fig. 48.—An iron-carbon-nickel diagram based on Fig. 48 is given in Fig. 49. It is assumed here that nickel carbide (Ni_3C) also appears—when it does appear—as a product of peritectic transformation. This
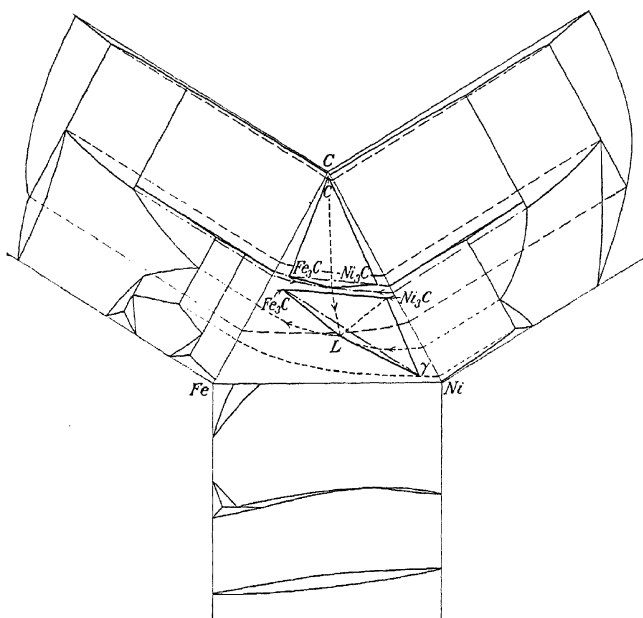
Fig. 49.—The iron-carbon-nickel diagram based on Fig. 48 and on the assumption that the carbides are stable.

assumption leads to the probability of two four-phase equilibria of the transition-plane type; *viz.*,

1. Carbon—nickel carbide—iron carbide—liquid.
2. Iron carbide—nickel carbide—gamma—liquid.

These are shown projected upon the basal triangle of Fig. 49. Other projections are omitted for clarity.

Inspection of Fig. 49 will show that this diagram is in accord with underlying principles if the carbides are either stable or persistent. Inasmuch as the free carbides are not stable, they

must exist—when they do—because of persistence, and this seemingly takes place only in the iron corner of the diagram.

Figure 50 is constructed on the assumption that the carbides do not exist; it is consequently much simpler than Fig. 49, and it is consistent with observed behavior of iron-carbon-nickel alloys over wide ranges of concentration and temperature.
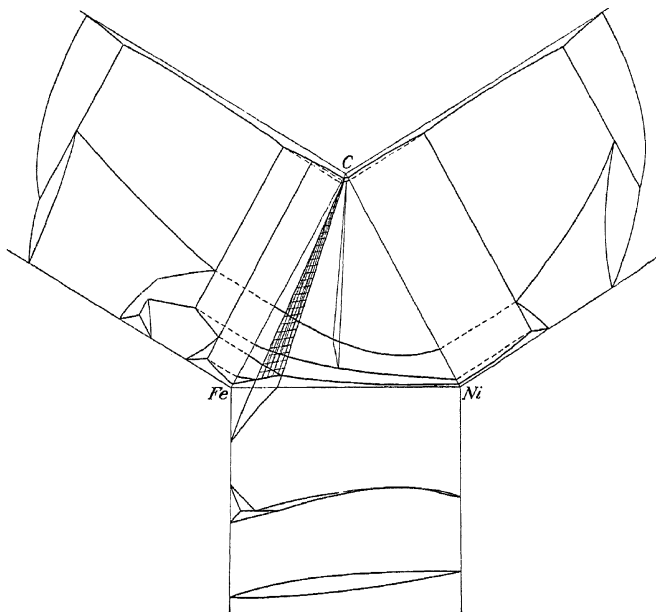
FIG. 50.—The iron-carbon-nickel diagram, based on Fig. 48 and on the assumption that the carbides do not exist.

Low-temperature sections of Fig. 50 are similar to corresponding sections of Fig. 34, which represents possibility IV (see page 66). It was stated that possibility IV is capable of plausible interpretation of the behavior of iron-carbon-nickel alloys; this is equally true of Fig. 50. (Sections of these diagrams become qualitatively identical by substitution of carbon for carbide wherever carbide is marked in sections of Fig. 34.)

Since the construction of the iron-carbon-nickel diagram depends upon the iron-carbon diagram selected and since Fig. 48, upon which Figs. 49 and 50 are based, differs from the generally

accepted diagram, the discussion of these diagrams will not be expanded.

40. Constitution of the Carbide.—Waterhouse[64] analyzed carbide separated electrolytically from a steel containing 0.97 per cent carbon and 3.75 per cent nickel with the following result:

Element	Percentage
Carbon	6.52
Nickel	1.86
Iron	91.71
Silicon	0.05

These values lead to the formula $(Fe,Ni)_3C$; *i.e.*, nickel may be substituted for some iron. To Waterhouse, therefore, belongs the credit for establishing the nature of the carbide which occurs in nickel steels.

Early references to carbides include that of Garrison[20] to Fe_3C and Ni_3C and that of Hadfield,[31] who suspected a ternary compound. Arnold,[185] however, found no evidence of a ternary compound but thought that he had isolated Ni_3C.

C. AUTHOR'S SUMMARY

1. All possibility of arriving at a most probable iron-carbon-nickel diagram collapses because of lack of information on the iron-carbon system and because of inadequate experimental work on the ternary system. The lack of a diagram, however, is felt slightly, if at all, by technology: useful alloys are restricted to a relatively narrow portion of the concentration triangle for which behavior is well enough known for most purposes.

There has been but one attempt to establish the diagram from experimental data. Inspection of these data and of the diagram derived (Fig. 25) leads to the conclusion that further work is necessary. The data themselves can be checked against results of other investigations over a narrow range only (Schichtel and Piwowarsky's line of twofold saturation originating in the iron-carbon eutectic). The two sets of results agree in trend; it is concluded, therefore, that some knowledge of the trend of this line of twofold saturation is about all that is to be winnowed from available data. This is not much upon which to base the diagram, but it is something.

2. If the contiguous binary diagrams of a ternary diagram are known, it is often possible to predict the nature of the ternary diagram. If there are even a few reliable solubility measurements on the ternary system, it is also often possible to predict with some confidence the locations of all of the solubility lines and surfaces. Of the three contiguous binaries of the iron-nickel-carbon diagram, however, only the iron-nickel diagram is established satisfactorily enough for the purpose.
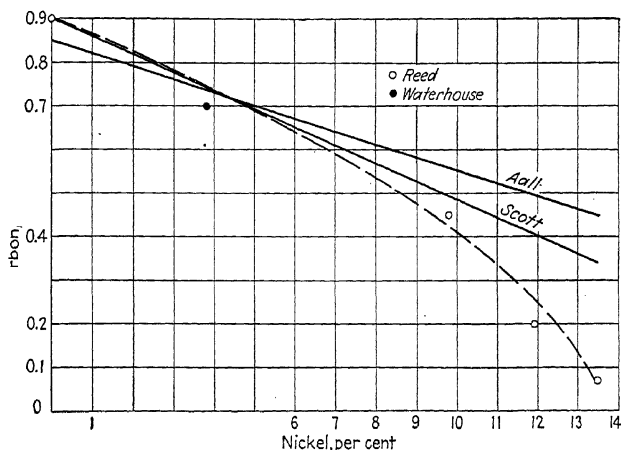
Fig. 51.—Variation with nickel content of the line of twofold saturation originating in the iron-carbon eutectoid. (*According to Aall*,[195] *Reed*,[428] *Scott*,[156] *and Waterhouse*.[54])

By considering the six phases which have been observed in iron-carbon-nickel alloys, their combinations, and the conventional iron-carbon and iron-nickel diagrams, five schematic possible ternary diagrams were constructed. The possible diagram based on the assumption that there exists a quasi-binary section Fe_3C-Ni (hence that there exists a partial ternary system Fe-Fe_3C-Ni) was found to contain a satisfactory working picture of the behavior of alloys of industrial importance. It is described in some detail, therefore, and explanatory sections were constructed.

3. Of practical interest is the "eutectoid" region of the diagram. This was shown to be simple, since the three-phase alpha-gamma-carbide space extends to the base of the ·prism.

Unfortunately, there are no data from which the boundaries of the three-phase space can be estimated, possibly excepting the gamma $\rightleftharpoons$ alpha-plus-carbide line which originates in the iron-carbon eutectoid. Estimated positions of this line are gathered in Fig. 51. Scott,[156] Aall,[195] and Reed[428] are agreed that the line moves in the direction of lower carbon content as nickel content is increased. Even if these data could be considered trustworthy, knowledge of variation of the line with temperature would still be lacking. There are data on transformation temperatures of industrial nickel steels, but they are not suitable for the purpose. It must be concluded, therefore, that position of the boundaries of the "eutectoid" region must await experimental work, preferably of the kind performed by Bain (Fig. 45).

4. In an attempt to obtain at least a hint of the direction in which lies the most promise of solution of the problem of the iron-carbon-nickel diagram, an unorthodox iron-carbon diagram was constructed. Experimental justification of this diagram is virtually so flimsy as to be non-existent: it consists of a few high-temperature measurements of solubility of carbon in iron. Errors of chemical analysis and of temperature measurement are to be expected, but they are the only data of utility in existence so far as is known. Presentation of such a highly speculative diagram seems to be justified on the ground that it might stimulate interest in the problem; its final solution probably will demand development of improved high-temperature technique.

CHAPTER IV

THE CONSTITUTION OF COMPLEX
IRON-NICKEL ALLOYS

*Alloys in Which the Third Component Is Metallic—Alloys in Which
the Third Component Is Non-metallic—Author's Summary*

Although the theory of ternary diagrams was formulated years
ago, it has been only within recent years that such diagrams for
metallic systems have become common.   Even so, few of them
have attained a state of precision that makes further investi-
gation unnecessary.   The reasons for this are so well known that,
in all probability, restatement is unwarranted.   For the benefit,
however, of the reader who is unfamiliar with the field, several of
the more important reasons may be repeated.   First, although
in principle the ternary diagram is no different from the binary,
it must be admitted that considerable study is ordinarily required
before the metallurgist feels at ease with it, and in most instances
his duties have not required that study.   This resulted in the
fact that many of the older diagrams were not constructed
according to the principles.   Second, experimental establish-
ment of a ternary diagram is a tremendous and exacting task,
fraught with further difficulties if there are many intermediate
phases.   This partly accounts for the number of partial diagrams
in existence.

So far as the ternary systems of which iron and nickel are
components are concerned, it is noteworthy that knowledge of
two of the most important is inadequate, *viz.*, iron-nickel-cobalt
and iron-nickel-chromium.   It is interesting to note also that
the reasons for the inadequacies are different: the iron-nickel-
chromium diagram has been investigated in considerable detail,
but recently found complexities invalidate much of the early and
some of the recent work, and the diagram remains to be put on a
quantitative basis; the iron-nickel-cobalt diagram has been
investigated so little that its quantitative side is mostly unknown.

Complex iron-nickel alloys are of interest mainly either
because of their resistance to heat or corrosive mediums, or of

83

their resistance to passage of electricity, or of their magnetic properties. So far magnetic properties account for the greatest number of compositions. These materials embrace the extremes of permeability, *i.e.*, the highest permeability materials, such as are used in communication equipment, and the lowest permeability materials, such as permanent magnets; consequently the constitution of these alloys is of considerable interest. There is still much to be done in the field but a good start has been made.

A. ALLOYS IN WHICH THE THIRD COMPONENT IS METALLIC

The complex systems consisting of iron, nickel, and another metallic element that have been investigated sufficiently to
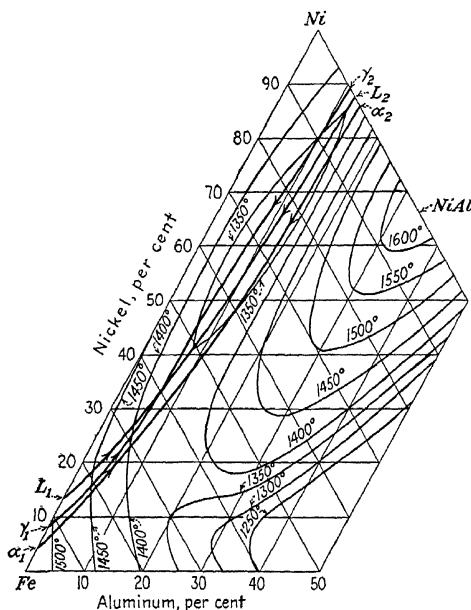
FIG. 52.—Liquidus isotherms and lines of twofold saturation of the iron-nickel-aluminum diagram.   (*Köster.*[457])

warrant review here contain aluminum, chromium, cobalt, copper, manganese, molybdenum, tungsten, and vanadium. Iron-nickel-aluminum alloys have come into prominence in recent years because of the permanent-magnet qualities of certain

ranges of composition. Chromium, copper, and molybdenum are often added because of special effects on high-permeability materials. Notable among the heat- and corrosion-resistant alloys are those containing iron, nickel, and chromium.

41. The Iron-nickel-aluminum Diagram.—The most recent work on the nickel-aluminum diagram, by Alexander and Vaughan,[586] indicates that four compounds exist. Of them,
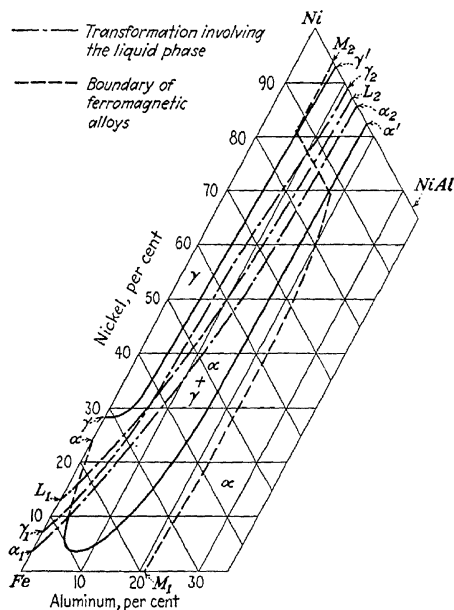
Fig. 53.—Room-temperature section of the iron-nickel-aluminum diagram.

only NiAl persists in the liquid state. Compounds Ni_3Al, Ni_2Al_3, and $NiAl_3$ appear as products of peritectic transformation. Compound Ni_3Al and nickel seemingly form a eutectic at about 83 per cent nickel. The iron-aluminum diagram is also complicated; this is in agreement with the general observation that aluminum is an enthusiastic former of intermetallic compounds.

The ternary system up to 50 per cent aluminum was investigated by Köster.[457] He concluded that NiAl and alpha iron are intersoluble since the structure of NiAl is body-centered cubic.
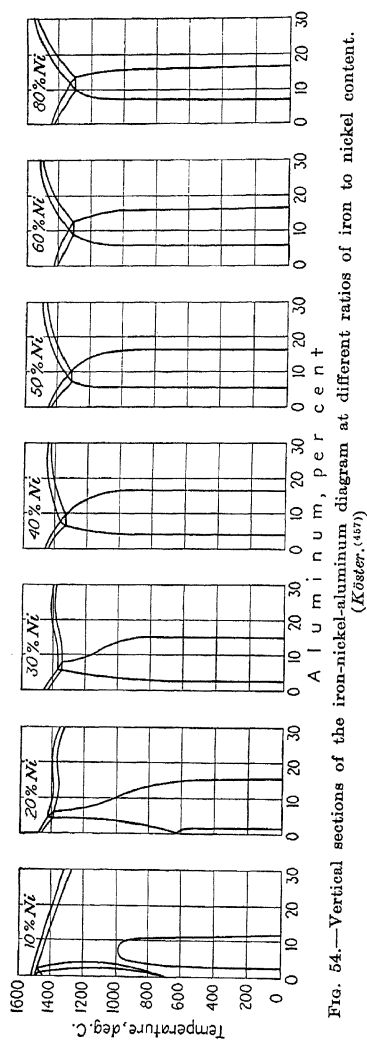
FIG. 54.—Vertical sections of the iron-nickel-aluminum diagram at different ratios of iron to nickel content.
(Köster.[457])

Experimental alloys were investigated by thermal analysis and by microscopic examination. Results of the former are given in Fig. 52, which shows the lines of twofold saturation originating in the iron-nickel peritectic transformation to proceed to the Ni-NiAl eutectic. The shift from peritectic-type to eutectic-type transformation appears to take place in the neighborhood of 33 per cent nickel and 7 per cent aluminum. Other lines in this diagram are liquidus isotherms.

Figure 53 shows a section of the iron-nickel-aluminum diagram at ordinary temperature, and Figs. 54 and 55 show various vertical sections. Figure 54 is for constant iron-nickel ratios; Fig. 55 is for constant aluminum contents. Figure 53 was modified recently by Bradley and Taylor[589] as a result of an X-ray study. New polyphase areas introduced are concerned mostly with superstructures, however.

Köster did not establish the directions of the tie lines of the alpha-gamma region. However, as a result of magnetic measurements he concluded that they lie at approximately constant aluminum content up to about 4 per cent aluminum and approximately constant iron content in the interval 0 to 45 per cent iron.

The irreversibility of the gamma-alpha transformation characteristic of iron-nickel alloys is found in the ternary alloys up to 7.5 per cent aluminum.

Köster's investigation has accomplished at least part of the preliminary work on the iron-nickel-aluminum diagram. The total diagram is bound to be complex and is likely to remain undetermined for some time.

42. The Iron-nickel-chromium Diagram.—This diagram is discussed in detail in "The Alloys of Iron and Chromium, Volume II,"* consequently a brief statement here is sufficient.

Although the subject of several extensive investigations, the iron-nickel-chromium diagram remains somewhat uncertain. For one thing, the latest investigators of the diagram, including the high-temperature portion, ignore the existence of the iron-chromium (FeCr?) compound. At least one investigation is known to be in progress which indicates that this compound persists over a considerable portion of the ternary area, consequently it cannot be ignored in any diagram that is intended to

* See footnote, p. 2.
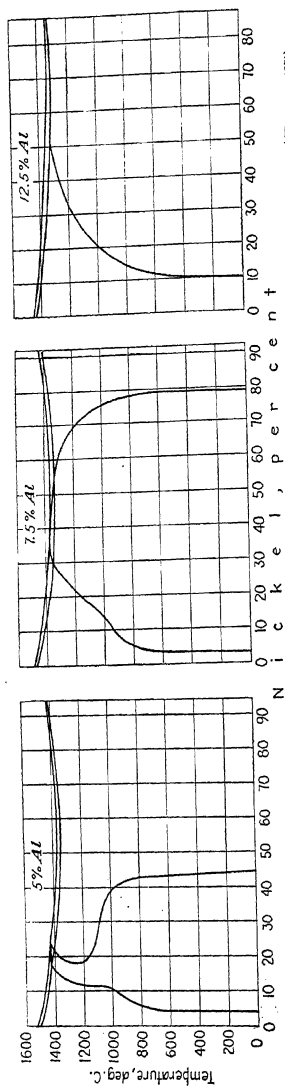
Fig. 55.—Vertical sections of the iron-nickel-aluminum diagram at 5, 7.5, and 12.5 per cent aluminum.   (Köster.[457])

be adequate. Reference is made, therefore, to the detailed discussion.

43. The Iron-nickel-cobalt Diagram.—The only iron-nickel-cobalt diagram based on experimental data was constructed by Kasé.[260] Alloys prepared from electrolytic materials were subjected to thermal and dilatometric analyses and microscopic examination. Before considering the results, it seems best to

Fig. 56.—Basal projection of a proposed iron-nickel-cobalt diagram. (*Kasé.*[260])

pause for a brief review of the iron-cobalt and nickel-cobalt diagrams. Both are complicated by polymorphic transformation of cobalt. One transformation was discovered by Masumoto,[236] who placed it in the vicinity of 400°C. upon cooling. The structure at lower temperatures is hexagonal (this may be called epsilon-phase cobalt), whereas the structure at higher temperatures is face-centered cubic. Kasé agreed with Masumoto that the face-centered cubic cobalt persists to the temperature of

melting and based his diagrams on this conclusion, but later work, especially by Seybolt and Mathewson,[542] indicates still further complication. They confirmed a second (high-temperature) transformation reported by Hendricks, Jefferson, and Schultz[342] and by Sykes[470] among others. The retransformation to the hexagonal structure was believed by Hendricks, Jefferson, and Schultz to occur at about 1020°C. and this temperature was confirmed by Sykes. Seybolt and Mathewson, however, arrived at a value of about 850°C. and this (for reasons given in their report) seems the more probable. It appears, therefore, that molten cobalt freezes in the hexagonal form—the form that is stable at room temperature also. Between, say, 450 and 850°C. the face-centered cubic form is the more stable, but the rate of transformation is so low that transformation may be prevented, as by even moderately rapid cooling. This digression is necessary to show that the cobalt corner of the diagrams constructed by Kasé cannot be correct and also to indicate the fact that interpretation of the behavior of cobalt-rich alloys may be made difficult by the uncertainty of determining their state.

Since there are no data which would permit construction of an iron-nickel-cobalt diagram, Kasé's is reproduced in Fig. 56, with the warning that future investigation is bound to produce marked changes.

44. The Iron-nickel-copper Diagram.—The extensive solubility gap of the iron-copper diagram (see Gregg and Daniloff[487] or Hansen[563]) is decreased and finally closed by nickel addition. Nickel and copper are completely intersoluble. Several determinations of the boundary of the gap at ordinary temperature and in the vicinity of freezing temperature have been reported; among them are those of Vogel,[89] Chevenard, Portevin, and Waché,[292] Kussmann and Scharnow,[307] Tasaki,[327] Dahl and Pfaffenberger,[444] Roll,[465] and Dahl, Pfaffenberger, and Schwartz.[525] The most complete information, however, was supplied by Köster and Dannöhl.[533] They prepared alloys from electrolytic copper, electrolytic nickel, and ingot iron by melting in a high-frequency furnace. Ingots were cold rolled, then annealed at a temperature near the melting point. The changes of electric resistance and of magnetization with temperature were then measured. From these data, and those of earlier investigators, the ternary diagram was constructed. This is

shown in projection in Fig. 57. The lines of negative slope in the lower left corner are associated with the peritectic transformation of iron. The paraboloid loop $\gamma_1 K M_1 Cu_1$ is the boundary of the solubility gap. Line KK' connects the critical points, as they change with temperature, of the gap. Line K_sU is the line of doubly saturated liquid phase that originates in the
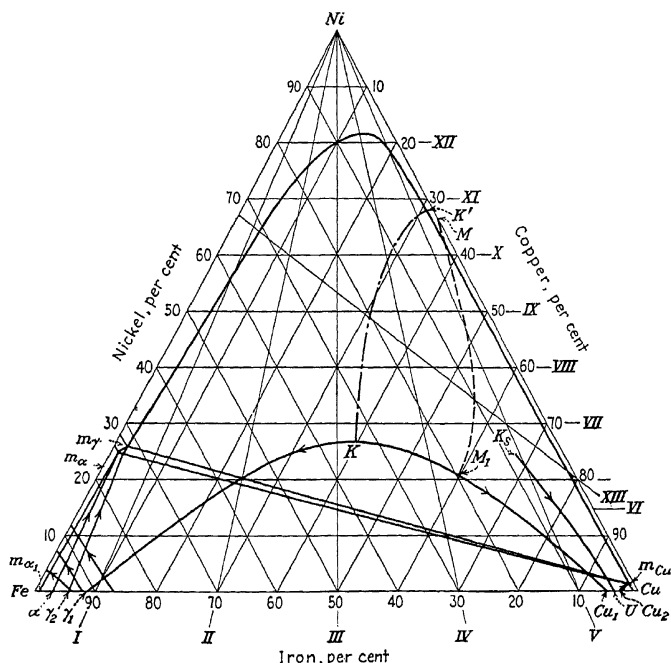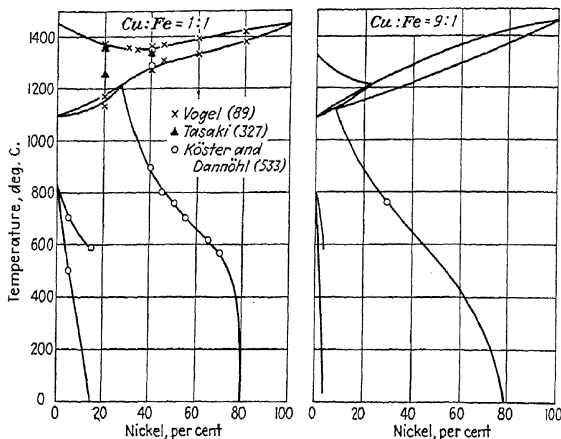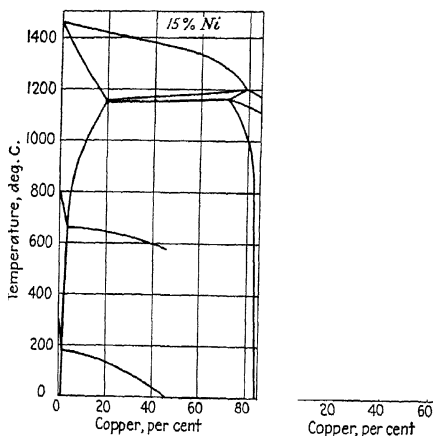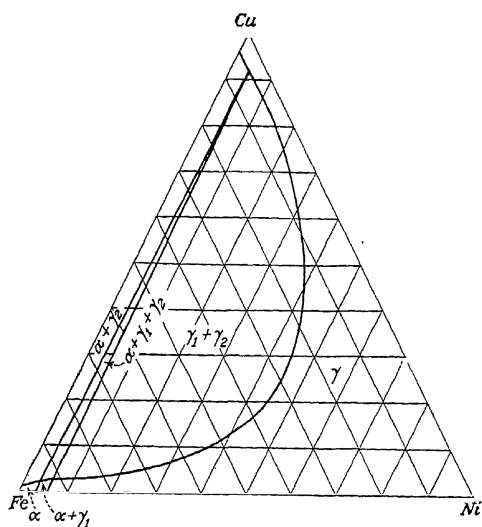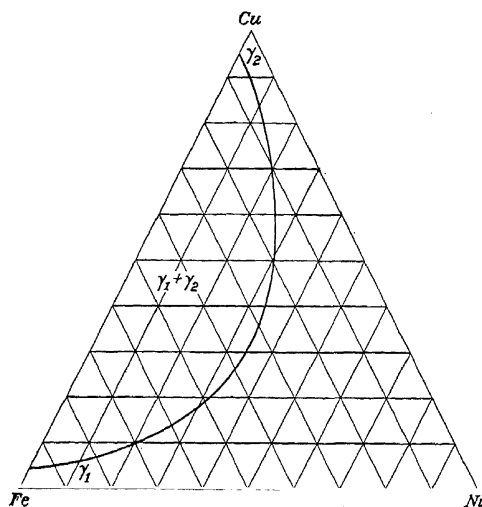
FIG. 57.—Basal projection of the iron-nickel-copper diagram. (*Köster and*
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

peritectic transformation at the copper-nickel end of the iron-copper diagram. This line terminates in the liquidus surface. This behavior is described in "Principles of Phase Diagrams,"[534] page 134.

Numbered straight lines in Fig. 57 indicate the location of vertical sections of the diagram; of these only III, V, VI, and VII (Figs. 58 and 59) are reproduced here. The meaning of these sections becomes clear from inspection of isothermic sections,

constructed from the vertical sections, the contiguous binary diagrams, and from the underlying principles.   Figure 60, the

FIG. 58.—Vertical sections III and V of the iron-nickel-copper diagram at ratios of copper to iron of 1:1 and of 9:1.   (*Köster and* .

FIG. 59.—Vertical sections VI and VII of the iron-nickel-copper diagram at 15 and 30 per cent nickel.   (*Köster and Dannöhl.*[533])

section at 800°C., shows consistency of the data on the solubility gap. The exact points of twofold saturation that bound the three-phase triangle are not known however. (The iron-rich

60.—Isothermic section at 800°C. (*Constructed from data of Köster and*

Fɪɢ. 61.—Isothermic section at 1000°C. (*Constructed from data of Köster and*

gamma phase is denoted γ_1; the copper-rich phase, γ_2.) This triangle, degenerated to a straight line, originates in the iron-copper eutectoid transformation. Figure 61, at 1000°C., above the temperature of the eutectoid transformation, shows only the solubility gap. The next section (Fig. 62), at 1200°C., lies above the copper-rich peritectic transformation but below the temperature of point K_s (Fig. 57). This results in the presence of a second three-phase triangle. There are no data to enable locating the boundaries of this triangle, but those shown

FIG. 62.—Isothermic section at 1200°C. (*Constructed from data of Köster and Dannöhl.* [533])

are consistent with the other experimental data. It is this three-phase region that gives rise to the lens-shaped region in the upper left portion of sections III and V and to the roughly triangular region in section VI. The final section, Fig. 63, at 1400°C., is no longer complicated by the intersection of any line of twofold saturation.

The vertical sections indicate that gamma-alpha transformation is no more reversible in iron-nickel-copper alloys than in iron-nickel alloys. This, so far, is of no great importance, because the alloys of interest for their magnetic and electric properties are of compositions such that the gamma-alpha trans-

formation does not participate. It is the solubility gap that counts in such materials.

The iron-nickel-copper diagram for the solid state can be regarded as reasonably well established. There is doubt attached to the region involving the liquid phase, but mostly on the quantitative side.

45. The Iron-nickel-manganese Diagram.—There are not enough data to enable construction of a reliable iron-nickel-manganese diagram. A considerable amount of work on the

Fig. 63.—Isothermic section at 1400°C. (*Constructed from data of Köster and*

iron-manganese diagram has been done recently, especially by Walters and his coworkers[547] and by Gayler.[447,596] Although similar to the iron-nickel diagram in several respects, *viz.*, in the region of liquid-solid equilibria and in the region of gamma-alpha transformation, the iron-manganese diagram is much more complicated, because of the three polymorphs of manganese. Furthermore, investigation of the iron-manganese alloys is difficult because their rate of transformation seems to be even less than that of iron-nickel alloys. Existing knowledge of the nickel-manganese diagram is much less adequate. The summarizing diagram of Hansen[563] indicates transformations in

the solid state, but their nature is a matter of conjecture.   In the region of liquid-solid transformation there is indication of a eutectic and a peritectic transformation, but this should be verified.

The only systematic investigation of the ternary system was reported as long ago as 1912 by Parravano[103] and this was confined to the liquidus and solidus surfaces.   The data indicate that the narrow temperature interval between the liquidus and solidus curves observed in iron-nickel and iron-manganese alloys persists in the ternary alloys.   They also indicate a marked temperature minimum as the nickel-manganese plane is approached.   The lowest melting temperature appears to have been in the neighborhood of 1000°C. and that only in the nickel-manganese plane.

· The alpha-gamma transformation of a few iron-nickel-manganese alloys was investigated by Scott,[398] but the results are not enough to enable construction of that part of the diagram; furthermore the extraordinary slowness of transformation that accompanies addition of more than a few per cent nickel or manganese to iron makes equilibrium determinations difficult or impossible except for compositions lying in the immediate vicinity of the iron corner of the triangle.

Thus, it is to be seen from the foregoing, future investigators of the iron-nickel-manganese diagram will work in nearly a virgin field.

46. The Iron-nickel-molybdenum Diagram.—The iron-molybdenum diagram is fairly well established, according to Gregg.[415] Two compounds appear as products of peritectic transformation; viz., Fe_3Mo_2 and FeMo, but only Fe_3Mo_2 persists to room temperature.   Data on the nickel-molybdenum system are much older, for it was in 1911 that von Baar[90] reported results of thermal analysis of alloys prepared from not very pure materials (97.9 per cent aluminothermic molybdenum and nickel containing 1.9 per cent cobalt).   The data are self-consistent enough, however, to indicate the appearance of compound NiMo as a product of peritectic transformation and a eutectic of NiMo and Ni at 51 per cent nickel and 1305°C.   Von Baar's data do not permit estimation of the solubility of molybdenum in nickel at the eutectic temperature, but a value of about 30 per cent molybdenum would be consistent.   The solubility declines, with

reduced temperature, to about 22 per cent, according to Köster and Schmidt.[497]

The ternary diagram was investigated by Köster,[496] although he restricted his alloys to those lying within the partial system Fe-Fe₃Mo₂-NiMo-Ni. (The section Fe₃Mo₂-NiMo cannot be quasi-binary, however, and was not assumed to be by Köster.) Materials and the methods of alloy preparation were not given,

Fig. 64.—The iron-nickel-molybdenum diagram. (*Redrawn from Köster.*[496])

but may be assumed to be adequate. Methods of analysis were dilatometry, magnetometry, microscopy, and precipitation-hardening tests.

Köster's results, in redrawn form, are given in Fig. 64. Parts of the contiguous binary diagrams have been added to show the terminals of the lines of doubly saturated liquid phase. Köster assumed the compounds Fe₃Mo₂ and NiMo to be completely intersoluble; this should be confirmed before acceptance. At any rate the assumption yields but one phase, marked theta, in addition to alpha, gamma, and the. liquid. The four phases participate in a transition-plane type of equilibrium at, accord-

ing to Köster's estimate, 1350°C. Three of the three-phase equilibria originate in the contiguous binary diagrams; the fourth (alpha, gamma, and theta phases) proceeds to the base of the prism, as is shown by the isothermic section at room temperature (Fig. 65). This section requires no comment.

The iron-nickel-molybdenum diagram cannot be considered to be established beyond question, but it seems likely that Köster's data present a fairly adequate picture of the behavior of at least alloys of the lower molybdenum contents.

FIG. 65.—Isothermic section at room temperature.   (*Köster*.[496])

47. The Iron-nickel-tungsten Diagram.—This diagram was investigated in considerable detail by Winkler and Vogel,[437] whose work was summarized at length by Gregg.[486]   It is not reviewed here, because no information has become available in the meantime that would effect change.

48. The Iron-nickel-vanadium Diagram.—Of the information on the iron-vanadium diagram, that supplied by Wever and Jellinghaus[367] is the most self-consistent and complete.   In brief, their data indicate a diagram similar to the iron-chromium diagram; *i.e.*, there exists a temperature minimum in the liquidus and solidus; there exists a gamma loop (the maximum solubility of vanadium in gamma iron is in the neighborhood of 1 per cent, however); and there exists an intermediate phase which appears only in the solid state and which may be the compound FeV.

The only data on the nickel-vanadium diagram were supplied by von Giebelhausen,[118] who investigated alloys containing less

Fig. 66.—Iron-nickel-vanadium phases existing at room temperature.   (*Störmer,*
as reported i

Fig. 67.—A schematic iron-nickel-vanadium diagram.

than 40 per cent vanadium.   These data indicate a minimum
in the liquidus and solidus at 21 per cent vanadium and 1355°C.

The only data of importance on ternary alloys were determined
by Störmer and reported by Kühlewein.[499]   These consist of the
results of X-ray measurement on alloys containing not more than
30 per cent vanadium; they are given in Fig. 66.   In the iron
corner with more than 25 per cent vanadium a lattice differing
from that of alpha or of gamma iron was observed, "which so
far has not been identified."   This lattice, however, was no
doubt that of the FeV(?) phase discovered by Wever and Jel-
linghaus.   Otherwise the results need no comment, possibly
excepting the fact that the required alpha-plus-gamma region was
found.

On the basis of the foregoing information the schematic iron-
nickel-vanadium diagram shown in Fig. 67 was constructed.
The peritectic transformation shown in the nickel-vanadium
diagram has not been found experimentally, but its existence is
highly probable.   The FeV(?) phase is shown to participate
in two three-phase equilibria rather than in the possible simpler
construction because Störmer found this phase in an alloy con-
taining 20 per cent nickel, consequently it is likely that future
investigation—if any—will disclose something of the sort shown.

B. ALLOYS IN WHICH THE THIRD COMPONENT IS NON-METALLIC

The non-metallic elements considered are hydrogen, phos-
phorus, silicon, and sulphur.   Inclusion of silicon in this list is
somewhat arbitrary because silicon is on the border line between
metallic and non-metallic elements; however, most of its proper-
ties are more non-metallic than metallic.

**49. Iron-nickel-hydrogen and Iron-nickel-chromium-hydro-
gen Alloys.**—The solubility of hydrogen in iron, nickel, chromium,
9 iron-nickel alloys, and 13 iron-nickel-chromium alloys as a
function of temperature was reported by Luckemeyer-Hasse and
Schenck.[422]   Data on iron-nickel alloys are given in Fig. 68.
The solubility of hydrogen, in terms of cubic centimeters at
standard temperature and pressure (0°C., 760 mm. Hg), was
found to be greater in gamma than in alpha iron.   This was true
also of iron-nickel alloys capable of gamma-alpha transformation,
although one containing 11.6 per cent nickel showed no indica-

tion of discontinuity. In the gamma-phase alloys, the solubility
of hydrogen increased with increased nickel content.

Data on iron-nickel-chromium alloys are given in Table 9 and
Fig. 69. These data are less easy to summarize in words because
of unorderly choice of compositions. Noteworthy, however,
and perhaps significant is the curve for alloy 1, which contained
3.1 per cent nickel and 2.57 per cent chromium. (This composi-
tion is selected because of its similarity to that of a group of

FIG. 68.—The solubility of hydrogen in iron-nickel alloys. (*Luckemeyer-Hasse*

useful steels, except for the low carbon content.) It is to be
seen that hydrogen solubility at 750°C. is less than half its value
at 800°C. This fact may be of some interest in the study of
flakes in forgings.

50. The Iron-nickel-phosphorus Diagram.—The iron-nickel-
phosphorus diagram up to about 15 per cent phosphorus was
investigated by Vogel and Baur.[400] Alloys were prepared from
electrolytic iron, low-carbon iron, electrolytic and shot nickel,
a 22.3 per cent phosphorus iron-phosphorus alloy, a 10 per cent
phosphorus nickel-phosphorus alloy, and red phosphorus by
melting 20-g. charges in small crucibles. The specimens were

subjected to thermal analysis and microscopic examination. Low-phosphorus, low-nickel alloys were homogenized by annealing 4 hr. at 1000°C. and high-phosphorus, high-nickel alloys were

FIG. 69.—The solubility of hydrogen in iron-nickel-chromium alloys. (*Lucke meyer-Hasse and ,*

heated at this temperature 48 hr. or more. Results permitted the construction of the partial iron—iron phosphide (Fe₃P)— nickel phosphide (Ni₃P)—nickel diagram; this is shown in pro-

TABLE 9.—COMPOSITION OF THE ALLOYS OF FIG. 69*

Alloy	Composition, per cent		
	C	Ni	Cr
1	0.01	3.1	2.57
2	0.01	8.12	4.43
3	0.01	11.4	3.02
4	0.01	26.4	2.79
5	0.01	5.1	4.65
6	0.01	10.0	4.63
7	0.01	5.16	9.53
8	0.01	20.3	9.66
9	0.01	15.1	14.6
10	0.01	10.0	29.5
11	0.02	2.04	44.1
12	0.02	5.1	44.2
13†	0.05	9.02	17.5

* Luckemeyer-Hasse and Schenck.[422]
† 0.93 per cent silicon and 0.45 per cent manganese.

jection in Fig. 70. The numbered straight lines indicate the location of vertical sections constructed (but not reproduced here).

It should be noted that the iron phosphide (Fe_3P)—nickel phosphide (Ni_3P) section is not quasi-binary, consequently the phosphides Ni_5P_2 and Fe_2P are not excluded.

The practical importance of this diagram could hardly justify the space which would be required to discuss it adequately, consequently the reader requiring details is referred to the original.

51. The Iron-nickel-silicon Diagram.—There is no information on the iron-nickel-silicon diagram. Because of the large number of intermediate phases in both the iron-silicon and the nickel-silicon system the ternary diagram is sure to be complex. One investigation is known to be in progress, but results are not yet available.

There is some information on the iron-nickel-silicon-carbon system, but it is of little value for constructing a diagram. Schichtel and Piwowarsky[321] prepared alloys containing up to about 16 per cent nickel and 5 per cent silicon, then investigated the solubility of carbon in them in the liquid state. Results may be summarized by the statement that the combined effect of

nickel and silicon in decreasing the solubility of carbon was equal to the sum of the effects of both elements when the alloy contained more than about 3 per cent silicon and 15 per cent nickel. When present in smaller amounts, the combined effect was less than the sum of both.

According to Söhnchen and Piwowarsky,[399] the combined effect of nickel and silicon in decreasing the solubility of carbon

Fig. 70.—The iron-nickel-phosphorus diagram.   (*Vogel and Baur.*[400])

in the gamma phase is equal to the sum of the separate effects up to 2 per cent silicon and 4 per cent nickel. These workers and Merz and Fleischer[356] gave data on the eutectoid transformation, but in both investigations the fact that such a transformation in a quaternary system is far from isothermic seems to have been overlooked. The meaning of their thermal and dilatometric data is therefore unknown.

52. The Iron-nickel-sulphur Diagram.—The partial ternary system iron—iron sulphide (FeS)—nickel sulphide (Ni_3S_2)—nickel was investigated by Vogel and Tonn.[328]   Alloys were

prepared from ingot iron or electrolytic iron, shot nickel, and sulphur by adding sulphur to molten iron-nickel alloys, then subjected to thermal analysis and microscopic examination. The behavior of the liquidus surface is indicated by the projections of Fig. 71. Line $S'Z'$ is the line of doubly saturated melt whose terminals lie in the peritectic transformations of the iron-nickel and iron-sulphur diagrams. E'_1 is the iron–iron sulphide eutectic. V' is associated with a transformation by which the ternary compound $(FeS)_2.Ni_3S_2$ is supposed to appear. E'_2 is the nickel–nickel sulphide eutectic. The intersection of the

Fig. 71.—Liquidus isotherms and lines of twofold saturation of the iron-nickel-sulphur diagram. (*Vogel and Tonn.*[328])

three lines originating in these points indicates four-phase equilibrium of the transition type.

Inspection of Hansen's[563] iron-sulphur and nickel-sulphur diagrams indicates that the iron-nickel-sulphur diagram for the solid state is more complicated than is shown by Vogel and Tonn. In addition, certain details as shown by them are to be viewed with suspicion, *e.g.*, the FeS-Ni$_3$S$_2$ section. However, this ternary diagram is hardly of enough importance to justify exhaustive description and discussion.

C. AUTHOR'S SUMMARY

1. There is considerable information on the constitution of complex iron-nickel alloys, but the amount is not proportional to the present practical importance of the alloys. The unsatisfactory status of the iron-nickel-chromium and the iron-nickel-cobalt diagrams may be cited as an example of this fact.

2. The review of existing information is somewhat cursory because it is believed that such a presentation is adequate for nearly all purposes. The reader requiring complete informa-

tion would be forced to the original sources anyway (since it is clearly impossible to reproduce here everything down to the last detail), consequently he is referred to those believed to be the most reliable. Wherever possible, however, attempt has been made to evaluate each diagram.

3. The iron-nickel-aluminum diagram is bound to be complicated because of the existence of a number of intermediate phases. Exploratory work on the iron corner is complete, nevertheless.

4. The status of the important iron-nickel-chromium diagram is unsatisfactory, but may be improved shortly.

5. The status of the iron-nickel-cobalt diagram is unsatisfactory also, but mainly because of insufficient information.

6. The iron-nickel-copper diagram is reasonably well established. The solubility gap of the iron-copper diagram is closed by nickel and there are no intermediate phases.

7. The status of the iron-nickel-manganese diagram is unsatisfactory. Experimental work on it is likely to be unusually difficult.

8. The iron-nickel-molybdenum and iron-nickel-tungsten diagrams are fairly well established.

9. The iron-nickel-vanadium diagram remains to be established experimentally. Enough is known, however, to permit construction of a schematic diagram.

10. Hydrogen is more soluble in nickel than in iron and its solubility in iron-nickel alloys increases with increasing nickel content. Data are given also on iron-nickel-chromium alloys, but they cannot be summarized.

11. The iron-nickel-phosphorus and iron-nickel-sulphur diagrams are probably established well enough for ordinary purposes.

12. The status of the iron-nickel-silicon diagram is unsatisfactory. It is known, however, that this diagram is complicated by intermediate phases.

CHAPTER V

PHYSICAL PROPERTIES OF IRON-NICKEL ALLOYS

Elastic Constants—Lattice Constants and Specific Volumes (Densities)—Thermal Properties—Author's Summary

By physical properties are meant those that are determined by ordinary physical measurement, but not those that can be called "mechanical" (such as tensile strength, yield strength, and reduction of area). Not all such properties are discussed here because there are enough data on some—*e.g.*, thermal expansion and electric and magnetic properties—to justify treating each in a separate chapter.

Relationships among the various physical properties of metals are becoming increasingly clear, although complete analysis is made impossible either by the lack of necessary data or by the fact that existing data are often of insufficient precision. The need is felt especially for iron-nickel alloys because of their many unusual properties. It seems almost certain that many of these properties would be far better understood if there existed reliable data by which theoretical deductions could be tested. This is necessary because their interrelations are seemingly too subtle for empiric treatment.

A. ELASTIC CONSTANTS

Determination of the elastic moduli in the principal crystallographic directions shows that iron crystals are anisotropic. For example, Cleaves and Thompson[520] quoted values of 19×10^6 lb. per sq. in. for the [100] direction, 31.4×10^6 lb. per sq. in. for the [110] direction, and 40×10^6 lb. per sq. in. for the [111] direction. In Chapter IX of this monograph (page 329) there is a suggested formula for computing polycrystalline magnetostriction from single-crystal data. An analogous formula for modulus of elasticity,

$$E = \tfrac{1}{5}(2E_{[100]} + 3E_{[111]})$$

yields 31.6×10^6 lb. per sq. in.   The accepted value for iron is about 30×10^6 lb. per sq. in.

There are no data on the moduli of elasticity in the principal crystallographic directions of nickel or of iron-nickel alloys. Further, excepting (Young's) modulus of elasticity, there is little information even on polycrystalline metal.

53. Modulus of Elasticity of Iron-nickel Alloys.—In the early studies of iron-nickel alloys considerable work was done on the effect of nickel on the modulus of elasticity of iron.   A large part of this was on irreversible alloys, with the result that many then

Fɪɢ. 72.—The modulus of elasticity of iron-nickel alloys.

unexplainable variations were observed.   In this review, selected values are based on the self-consistent data of Guillaume,[24,26] Honda,[144] Nakamura,[535] and Engler.[617]   Values obtained by Zacharias[474] and by Engler for nickel, which fall within the range given by Merica,[572] are selected as representative of nickel.   Excluded from consideration are data of Mercadier,[15] Howard,[16,21,28,32] Rudeloff,[29] Angenheister,[44] Carpenter, Hadfield, and Longmuir,[59] Müller,[179] Nishiyama,[312] and other workers.   The data considered are given in Fig. 72, and curves indicate selected values.   These show the modulus of elasticity of alpha-phase alloys to decline linearly from about 30×10^6 lb. per sq. in. for iron to about 22×10^6 lb. per sq. in. for the 30 per cent nickel alloy.   The values for gamma-phase

alloys are somewhat higher in the composition range in which either phase or both may exist. The ones for higher nickel (gamma-phase) alloys increase rapidly, then more slowly, from about 21×10^6 lb. per sq. in. at 35 per cent nickel to about 30×10^6 lb. per sq. in. for nickel. Thus, for alloys that are definitely alpha phase and for those definitely gamma phase the modulus of elasticity is fairly well established.

54. Poisson's Ratio.—There are no direct measurements of Poisson's ratio for iron-nickel alloys. Honda[144] determined the moduli of elasticity and rigidity, however, and this permits computation of the ratio by means of the relation

$$G = \frac{E}{2(1 + \sigma)}$$

where G is the modulus of rigidity, E is the modulus of elasticity, and σ is Poisson's ratio. Such computation yields values in the neighborhood of 0.29 for most of Honda's alloys; his value for iron (0.23), which is certainly too low, and those for alloys in the 25 to 40 per cent nickel region diverge. For example, Honda's data yield a value of 0.12 for his 36.9 per cent nickel alloy. Whether or not the ratio undergoes sharp decline in the "invar" region is open to question. A check is provided by Mehl's[283] determination of the compressibility of a 36 per cent nickel alloy (in metric units and at room temperature) of 0.85×10^{-6}. This is equivalent to a bulk modulus of 16.7×10^6 lb. per sq. in. Assuming the modulus of elasticity of this alloy to be 21×10^6 lb. per sq. in., Poisson's ratio becomes 0.29 (from the relation $K = E/3(1 - 2\sigma)$, where K is the bulk modulus). This indicates that Poisson's ratio undergoes slight change with composition. This seems more likely than the indication of Honda's data; consequently suggested values are 0.285 for iron, 0.29 for the 36 per cent nickel alloy, and 0.30 for nickel.

55. Modulus of Rigidity, Bulk Modulus, and Compressibility of Iron-nickel Alloys.—The only data on the modulus of rigidity of iron-nickel alloys were given by Honda[144] and by Honda and Tanaka.[232] These are shown in Fig. 73; the curves represent values computed from the selected moduli of elasticity and the assumption that Poisson's ratio increases linearly from 0.285 for iron to 0.3 for nickel. This is consistent with the observed compressibility of a 36 per cent nickel alloy. If it is

true that Poisson's ratio becomes relatively small in the vicinity of 35 per cent nickel, as is indicated by Honda's data, the computed value for 35 per cent nickel is low by about 1×10^6 lb. per sq. in.   It seems more likely however, as is stated above, that the ratio undergoes no great change with composition; hence, that the curve is a reasonably reliable approximation.

Until very recently there existed only the one determination of the bulk modulus for an iron-nickel alloy mentioned before, viz., 16.7×10^6 lb. per sq. in. for a 36 per cent nickel alloy reported by Mehl.[283]   Computation of Poisson's ratio from this value and the selected modulus of elasticity, and

FIG. 73.—Observed moduli of rigidity compared with computed values.

from the observed compressibilities of iron and nickel, led to suggested values which are given in Table 10.   From these ratios and the selected moduli of elasticity, values for bulk modulus and compressibility were computed.   For completeness, computed moduli of rigidity are given also.   Directly determined compressibilities of iron-nickel alloys, reported recently by Ebert and Kussmann,[593] are given in Table 11.   Deviation from those given in Table 10 is marked in the 31 to 50 per cent nickel range.   The value for 35 per cent nickel corresponds to a bulk modulus of 11.6×10^6 lb. per sq. in. and a Poisson's ratio of about 0.2.   These data are not impossible, but they are certainly to be viewed with suspicion, at least until verified by measurements of the kind believed to lead to reliable results.   Mehl's determination also should be verified before complete acceptance.

TABLE 10.—SUMMARY OF ELASTIC CONSTANTS OF POLYCRYSTALLINE IRON-NICKEL ALLOYS

Nickel, per cent	Poisson's ratio (σ), suggested	Modulus of elasticity, E, 10^6 lb./ sq. in.	Modulus of rigidity, G, 10^6 lb./ sq. in.	Bulk modulus, K, 10^6 lb./sq. in.	Compressibility, β, 10^{-6} sq. cm./kg.
0	0.285	30.1	11.7	23.3	0.61
10	0.285	27.5	10.7	21.3	0.67
20	0.285	24.9	9.7	19.3	0.74
30	0.290	22.1	8.6	17.5	0.81
35	0.290	21.0	8.1	16.7	0.85
40	0.290	21.3	8.3	16.9	0.84
50	0.290	23.9	9.3	19.0	0.75
60	0.295	26.2	10.1	21.3	0.67
70	0.295	27.6	10.7	22.4	0.64
80	0.295	28.6	11.0	23.3	0.61
90	0.300	29.4	11.3	24.5	0.59
100	0.300	30.1	11.5	25.0	0.57
20*	. . . . .	28.4	11.0	22.0	0.65
30*	. . . . .	23.5	9.1	19.7	0.76

* Gamma-phase alloy.

TABLE 11.—COMPRESSIBILITY OF SOME IRON-NICKEL ALLOYS*

Nickel, per cent	Compressibility, 10^{-6} sq. cm./kg.
0	0.600
11.4	0.633
19	0.720
29.7	0.84
30	0.84
31	1.11
33	1.23
35	1.23
40	1.2
50	1.20
60	0.75
73	0.75
87	0.66
100	0.531

* Ebert and Kussmann.[593]

56. Temperature Coefficients of the Elastic Constants.—The definition of the temperature coefficients of the elastic constants is of the form

$$u = \frac{1}{A_0} \frac{dA}{dt}$$

where a is the temperature coefficient, A is the elastic constant, and t is the temperature.

There are enough data on the temperature coefficient of the modulus of elasticity at room temperature to indicate its variation with composition. Those shown in Fig. 74 were determined by Guillaume,[275] Keulegan and Houseman,[455] and Engler.[617] That there is a range of composition for which the temperature coefficients are positive in sign is fully substantiated by the three

Fig. 74.—The temperature coefficient of the modulus of elasticity at room temperature.

sets of data. This behavior seems to persist to the temperature of magnetic inversion, as is shown by Engler's curve for a 42 per cent nickel alloy (Fig. 75). The temperature coefficients for higher nickel alloys, such as those containing 50 and 78.5 per cent nickel, appear to be negative for all temperatures, and the coefficients for the 93 per cent nickel alloy and for nickel, although negative at ordinary temperature, become positive as the magnetic-inversion temperature is approached. A similar curve for nickel was obtained earlier by Zacharias.[474] The curve for alpha-phase alloys shown in Fig. 74 is based upon an average value for iron and data of Keulegan and Houseman and of Kimball and Lovell.[216] Values of $\Delta E/E$ of the latter were used to compute E_0 at 3.5 per cent nickel. The computed e_0, -26.5×10^{-5} per °C., is in excellent agreement with

Keulegan and Houseman's datum of -27×10^{-5} per °C. The curve for alpha-phase alloys, actually for 0°C., is probably valid also for 20°C., because Engler's curve for the variation of the modulus of elasticity with temperature of iron indicates no appreciable difference of the temperature coefficient over the 0 to 20°C. range.

FIG. 75.—The variation with temperature of the modulus of elasticity of some iron-nickel alloys. (*Engler.*[517])

In passing, it may be noted that the data of Keulegan and Houseman given in Table 12 indicate that the temperature coefficient of the modulus of elasticity in the vicinity of ordinary temperature is relatively insensitive to the heat treatment of the material.

Various attempts have been made to obtain analytic expressions for the variation of the modulus of elasticity with tempera-

Table 12.—Temperature Coefficient of the Modulus of Elasticity
of Some Alloys Containing Nickel*

Mark	Composition, per cent				Condition	Temperature coefficient of the modulus of elasticity at 0°C., $e_0 \times 10^5$	Ratio of coefficients, at 25 and -25°C., e_{25}/e_{-25}
	Mn	Ni	Cr	W			
8a	0.13	0.48	4.97		Annealed	−28.4	1.06
8b	0.13	0.48	4.97		Tempered	−26.0	1.10
9a	0.18	0.48	3.50		Annealed	−27.0	1.08
9b	0.18	0.48	3.50		Tempered	−27.1	1.09
31	0.84	1.5	32.7	11.1 3.9	Hard drawn	−6.6	
32	0.16	0.18	34.9	0.12	Hard drawn	+48.2	

* Keulegan and Houseman.[465]

ture. For example, Widder[402] used an exponential function, but the behavior of ferromagnetic substances makes such functions of doubtful value. A case in point is the modulus-temperature curve of nickel, which, according to Zacharias[474] and to Engler,[617] passes through a minimum in the neighborhood of 200°C., then a maximum at the temperature of magnetic inversion.

An interesting and important example of control of the temperature coefficient (and control to any useful extent is seldom possible) is provided by alloys known as *elinvars* and discovered by Guillaume.[146] By substituting about 12 per cent chromium for a like amount of iron in iron-nickel alloys, it was found that the curve of Fig. 74 was displaced in a way such that its maximum appeared at a point representing a temperature coefficient of approximately zero. This fact is very important to the makers of springs for watches and clocks for a reason that is clear. In addition to freedom from temperature effects, these alloys are virtually non-magnetic and have high resistance to corrosion. The original elinvar composition has been modified; according to Shubrooks,[434] most of it now used contains 31 to 33 per cent nickel, 4 to 5 per cent chromium, 1 to 3 per cent tungsten, and 0.5 to 2 per cent manganese, silicon, and carbon. Alloy 31 of Keulegan and Houseman was of the elinvar type, but its composition was different, as may be seen by inspection of Table 12. Even so, the temperature coefficient (-6.6×10^{-5} per °C.) was much smaller than that of ordinary materials.

Data on the temperature coefficient of the modulus of rigidity of 28 iron-nickel alloys were given by Chevenard.[145]   These are reproduced in Fig. 76.   The behavior of this coefficient is evidently similar to that of the temperature coefficient of the modulus of elasticity.   It is of interest that the maximum of the curve progresses to higher nickel contents as temperature

FIG. 76.—The temperature coefficient of the modulus of rigidity at various temperatures.

is increased.   That Keulegan and Houseman's values for 3.5 and 5 per cent nickel alloys agree with those of Chevenard is to be noted also.   Other data given by Chevenard[250] on alloys containing 5, 10, and 15 per cent chromium show that the maximum of the curve of the temperature coefficient of the modulus of rigidity is displaced with increasing chromium content in a manner analogous to that described for the temperature

coefficient of the modulus of elasticity. With 15 per cent chromium, the coefficient is negative in sign for all nickel contents.

Other data, on 36 per cent nickel alloys, showed dependence on treatment. For all treatments, however, values of $\Delta G/G$ were maximum in the vicinity of 250°C., an observation made earlier by Guye and Woelfle.[70]

There are no data on the temperature coefficients of the bulk modulus and of Poisson's ratio of iron-nickel alloys.

57. Effect of Cold Work on Modulus of Elasticity.—The effect of cold work on the modulus of elasticity of iron, steel, and certain of the non-ferrous metals has been investigated by a number of workers, but it is sufficient here to cite Kawai's[349] report, which included results on one 3 per cent nickel steel. In brief, the modulus of iron, carbon steel, and nickel steel was decreased, first rapidly, then slowly, by increasing degrees of cold work by stretching. The modulus of aluminum, copper, and nickel first decreased, then increased (an effect of crystal structure?).

B. LATTICE CONSTANTS AND SPECIFIC VOLUMES (DENSITIES)

From the standpoint of thermodynamics, specific volume is one of the fundamental properties of substances. Furthermore, the volume-mass relationship is probably known to all persons in one way or another, for density (the reciprocal of specific volume) is perhaps the easiest derived property for the senses to observe. Lattice dimensions can be computed from specific volumes, but can be determined directly with far more accuracy. The computation then is generally to specific volumes (or densities) from lattice constants.

58. Lattice Constants of Iron-nickel Alloys.—Iron-nickel alloys were first investigated by X-rays by Andrews[158] for the purpose of identification of phases. The first systematic investigation was made by McKeehan,[198] using 14 alloys in various conditions of treatment. Because of the relatively low precision of the apparatus at that time, results were only semi-quantitative; they did indicate, however, that the lattice constant of gamma-phase alloys becomes smaller as 100 per cent nickel is approached. This was amply verified by subsequent work. A larger number of alloys was studied by Osawa[240] with results that were much more self-consistent than those of McKeehan, but the values

are generally higher than those indicated by the latest work. Data on 10 alloys reported by Jung[259] are of precision comparable with that of McKeehan's measurements (again because of inadequacies of the apparatus of that time), consequently need not be examined in detail.

Lattice constants of a few alpha-phase alloys were measured over a range of temperature by Roberts and Davey.[359] To them, therefore, is due the credit for first attacking the difficult

Fig. 77.—Lattice constants of gamma-phase iron-nickel alloys at room temperature.

problem of determining the lattice constants of iron-nickel alloys at elevated temperatures.

The first lattice constants to be verified by later work were reported by Phragmén[394] for nine alloys containing from 20 to 50 per cent nickel and for the temperature range of 10 to 300°C. These are given in Table 13.

In 1936 and 1937 there appeared three extensive reports of X-ray studies of iron-nickel alloys—prepared from materials and by methods that are conducive to high purity—that are in substantial agreement. The first of these was by Jette and

Foote;[566] the others, by Bradley, Jay, and Taylor[588] and by Owen, Yates, and Sully,[606] appeared only shortly thereafter. Results for gamma-phase alloys at room temperature are given in Fig. 77. Jette and Foote's data indicate a linear variation of lattice constant with composition from about 43 to 100 per cent nickel, but those of the other workers show a small negative deviation that is greatest somewhere between 75 and 80 per cent nickel. X-ray data from these three laboratories ordinarily

TABLE 13.—LATTICE CONSTANTS OF IRON-NICKEL ALLOYS AT VARIOUS TEMPERATURES*

Nickel, weight percentage	Nickel, atomic percentage	Lattice constants, Å., at various temperatures							
		a	°C	a	°C	a	°C	a	°C
29.44	28.42	3.5753	10	3.5821	125	3.5885	195	3.5973	295
34.28	33.17	3.5834	10	3.5848	110	3.5898	195	3.5966	295
37.92	36.76	3.5883	10	3.5895	110	3.5908	190	3.5976	295
36.00	34.86	3.5863	10	3.5873	110	3.5910	195	3.5960	295
20	19.21	3.572†	10	......	...	......	...	3.596‡	300
50.4	49.15	3.5794	10	3.5822	105	3.5855	190	3.5901	290
		3.5777	10						
35.8	34.67	3.5848	10	......	...	3.5868	180	3.5921	280
		3.5841	10						
36.40	35.26	3.5853	10	3.5860	105	3.5876	180		
		3.5851	10						
35.52	34.39	3.5846	10	3.5853	105	3.5865	180		
		3.5846	10						
100	100	3.5180	18						

* Phragmén.[394]
† Body-centered phase: $a = 2.862$.
‡ Body-centered phase: $a = 2.874$.

are so consistently in agreement that the difference here probably arises out of something other than experimental error. The only suggestion so far is that the difference is connected with the fact that the samples of Jette and Foote were quenched at very high velocity.* Among the other possibilities are superstructure and magnetic changes, but it would be premature to pursue the matter.

The lattice-constant curve passes through a maximum at about 38 per cent nickel, then declines. It is impossible to

* Private communication.

determine the course of the curve experimentally below about 25 per cent nickel, but extrapolation for gamma iron at room temperature (3.562 Å.) indicates virtually a linear relation, according to the data of Jette and Foote. Inspection of Fig. 77 shows the possibility of a somewhat higher value, perhaps 3.570 Å.; this point is discussed later.

FIG. 78.—Lattice constants of gamma-phase iron-nickel alloys at various temperatures. (*Owen, Yates, and Sully.*[606])

Lattice constants for temperatures up to 600°C. were determined by Owen, Yates, and Sully and are given in Fig. 78. It is noteworthy that the maximum is shifted to higher nickel contents with increasing temperature until it finally disappears in the neighborhood of 400°C. However, even at 600°C. the deviation from rule-of-mixtures values is unusual.

Lattice constants of alpha-phase alloys at 25°C. determined by Jette and Foote and by Owen, Yates, and Sully are given in

Fig. 79; agreement is reasonably good, and it is definite that the lattice of iron is expanded by the addition of nickel. Results for elevated temperatures, again by Owen, Yates, and Sully, are given in Table 14.

On the whole, therefore, the lattice constants of gamma-phase alloys are fairly well established, although their interpretation is another matter. Further work, especially at elevated temperatures, in the alpha and alpha-plus-gamma regions would be very useful.

FIG. 79.—Lattice constants of alpha-phase iron-nickel alloys at 25°C.

59. Specific Volume of Iron-nickel Alloys: Density.—As a basis of comparison for the various specific-volume data (for room temperature), a curve was constructed from values computed from the lattice constants of Jette and Foote.[566] This is shown in Fig. 80. Recently reported X-ray densities of Owen, Yates, and Sully[606] are in good agreement. The broken line in the high-iron region is of course partly imaginary, but is useful in showing the deviation from the rule of mixtures (which operates for perfect solutions). This is discussed later. The direct density measurements shown are those of Guillaume,[24] Hegg,[84] Chevenard,[109] Osawa,[240] and Nishiyama.[312] Virtually all points lie above the curve for computed values, which is the expectation. In addition, all of Chevenard's points, and some of those of Nishiyama, lie very near the curve; this indicates that the curve is a close approximation to true limiting values for gamma-phase alloys.

The shape of the specific-volume curve of gamma-phase iron-nickel alloys is very unusual. The usual observation is that such

curves are either straight lines (for ideal solutions) or paraboloid curves. The iron-nickel alloy curve, however, is straight or nearly so from 0 to about 25 per cent nickel, and again straight

FIG. 80.—The specific volume of iron-nickel alloys.

from about 50 to 100 per cent nickel. Lattice constants determined by Bradley, Jay, and Taylor[588] indicate possible negative deviation from the straight line that is maximum at about 80 per cent nickel. In terms of specific volume, the maximum deviation

TABLE 14.—LATTICE CONSTANTS OF ALPHA-PHASE IRON-NICKEL ALLOYS AT ELEVATED TEMPERATURES*

Nickel, per cent	Lattice constant, Å., at						
	15°C.	100°C.	200°C.	300°C.	400°C.	500°C.	600°C.
0	2.8605	2.8634	2.8672	2.8712	2.8756	2.8803	2.8855
3.1	2.8621	2.8649	2.8685	2.8723	2.8764	2.8809	2.8857
9.0	2.8634	2.8662	2.8695	2.8730	2.8768	2.8806	2.8845
16.7	2.8630	2.8655	2.8689	2.8725	2.8764	2.8804	2.8844
24.2	2.8630	2.8655	2.8686	2.8721			

* Owen, Yates, and Sully.[ ]

from the value of Jette and Foote is of the order of only 0.0001 cu. cm. per g.

The course of the specific-volume curve of alpha-phase alloys is not clear. The values computed from the lattice constants of Jette and Foote indicate a maximum at 2 per cent nickel, but the scatter of the experimental points is such that no definite statement can be made. Furthermore, the infinite number of possible

Fig. 81.—The specific volume of iron-nickel alloys, computed from X-ray data.

proportions of gamma and alpha phases in alloys containing more than between 5 and 10 per cent nickel complicates matters hopelessly.

60. Influence of Temperature on Specific Volume.—Recent X-ray measurements of Owen, Yates, and Sully [606] permit computation of specific volumes of gamma-phase iron-nickel alloys at elevated temperatures. These are shown in Fig. 81, for 200, 400, and 600°C., together with the selected curve for 20°C. and an estimation of the curve for absolute zero. The latter should

be fairly reliable for alloys containing more than 35 per cent nickel, because it is based on fairly reliable expansion data.

Of interest is the disappearance of the maximum volume somewhere between 20 and 200°C. It is interesting also to note that even at 600°C. there is evidence that the curve contains two linear portions of different slope. This indicates that the unusual behavior of iron-nickel alloys persists at temperatures at which they are not ferromagnetic. The extrapolated values of hypothetical specific volume of gamma iron indicate very high low-temperature thermal expansion. Linear extrapolation, therefore, may not be justified.

FIG. 82.—The specific volume of alpha-phase iron-nickel alloys, computed from X-ray data. (*Owen, Yates, and Sully.*[606])

Specific volumes for alpha-phase alloys are given in Fig. 82. These computed values (from X-ray data) also are consistent with the observed temperature coefficients.

61. Specific Volume of Molten Iron-nickel Alloys.—The deviation of specific volumes from rule-of-mixtures values of iron-

FIG. 83.—The specific volume of molten iron-nickel alloys. (*Based on data of Benedicks, Ericsson, and Ericson.*[291])

nickel alloys in the solid state persists in the liquid state, according to data of Benedicks, Ericsson, and Ericson[291] given in

Fig. 83.   Points therein represent experimental data; the curves differ somewhat from those constructed by Benedicks and his coworkers.   Because of the nature of such measurements at high temperatures great accuracy is not to be expected.   However, positive deviation is definite and there is indication that alloys in the vicinity of 30 per cent nickel have negative coefficients of expansion.   This indication should be verified before acceptance, because inspection of the original measurements leads to the conclusion that deviation of the usual kind (*i.e.*, for which curves are regular) is not excluded.   If, however, the data of Benedicks, Ericsson, and Ericson are confirmed, alloys of the invar range of composition must be placed among the curiosities of which water between 0 and 4°C. is a member.

62. Specific Volume or Density of Other Alloys.—Density values for some iron-nickel-cobalt alloys, reported by McKeehan,[601] are given in Table 15.   These data are too few to permit generalization.   This is true also of the diagram given by Kühlewein[499] for iron-nickel-vanadium alloys containing up to about 30 per cent vanadium.

So far as structural steels are concerned, it may be expected that their density is not very different from that of the corresponding carbon steels, although changes are effected by heat treatment and mechanical working.   Andrew and Dickie,[228] for example, found the specific volume of quenched nickel steels to be decreased by tempering, but the actual values are hardly of interest here.   This is likewise true of the investigation of Schulz[114] on the effect of quenching and of that of Houdremont and Burklin[257] on the increase of specific volume upon cold drawing.   A good example of the fact that considerable variation of composition of steels can be made without appreciable change of specific volume ascribable only to composition is provided by a value of 7.864 g. per cu. cm. for the density of a steel containing 3 to 5 per cent nickel, 12 to 14 per cent manganese, and about 0.5 per cent carbon, in the rolled condition, reported by Hall.[381] This density corresponds to a specific volume of 0.1271 cu. cm. per g., which is the selected value for iron at room temperature.

For completeness, representative values are given for nickel cast irons, selected after inspection of data by Everest, Turner, and Hanson,[252] Kötzschke and Piwowarsky,[279] and Bornhoffen and Piwowarsky.[441]   These are: for nickel up to about 5 per

TABLE 15.—DENSITY OF IRON-NICKEL-COBALT ALLOYS AT ROOM
TEMPERATURE*

Composition, per cent			Density, g. per cu. cm.	Specific volume, cu. cm. per g.
Ni	Co	Mn		
79.29	10.21	0.46	8.796	0.1137
69.38	20.20	0.42	8.793	0.1138
64.56	14.84	0.33	8.633	0.1159
61.19	28.38	0.19	8.748	0.1143
60.05	24.79	0.32	8.703	0.1150
50.79	38.66	0.31	8.741	0.1144
50.26	25.04	0.27	8.574	0.1167
40.19	10.21	0.32	8.309	0.1205

* McKeehan.[501]

cent, density = 7.4 g. per cu. cm. (specific volume = 0.135 cu. cm. per g.); for nickel up to 40 per cent (austenitic cast irons), density = 7.55 g. per cu. cm. (specific volume = 0.132 cu. cm. per g.).

C. THERMAL PROPERTIES

In this portion the data on specific heat and thermal conductivity of iron-nickel alloys are reviewed. Compared with most other substances, these alloys are decidedly "anomalous" in their thermal behavior. In general, as is indicated many times elsewhere, the unexpected is the rule in the iron-nickel system.

63. Specific Heat (Heat Capacity).—The specific heat of iron-nickel alloys, in common with other ferromagnetic substances, differs from that computed on the basis of early theory because of components other than lattice vibration (c_L). Characteristic of these substances is the "magnetic" component (c_M), which is connected with the decrease of spontaneous magnetization with increasing temperature, and which rises to a sharp maximum in the neighborhood of the magnetic-inversion temperature, then falls rapidly (but does not disappear until a temperature somewhat above the inversion is reached). In a sense, therefore, magnetic specific heat is an electronic specific heat, but for the purpose of this description Stoner[582] and others will be followed in their custom to restrict electronic specific heat (c_E) to that component arising out of changes of translational states of

electrons (as opposed to changes of orientation). The c_E component exists for all metals, although there is evidence that it is larger for the ferromagnetic metals.

The foregoing are best considered components of the specific heat at constant volume (c_V), which is obtained from the measured specific heat, at constant pressure (c_P), by application of the "dilatation correction" $(c_P - c_V)$. The total specific heat at constant volume is composed of the three components: $c_V = c_L + c_M + c_E$.

64. Specific Heat of Nickel.—Agreement of available data on the specific heat of nickel at low temperatures is good, as may be

FIG. 84.—The specific heat of nickel at low temperatures.

seen by inspection of Fig. 84, which includes measurements of Rodebush and Michalek,[222] Lapp,[280] Eucken and Werth,[336] and Clusius and Goldmann.[521] Not all points were plotted because of excessive crowding, but those shown are sufficient to indicate that the curve is satisfactorily established.

Values for the specific heat at high temperatures are given in Fig. 85; these were selected after examination of a plot of data reported by Tilden,[35] Dumas,[72] Schimpff,[88] Schübel,[113] Weiss, Piccard, and Carrard,[123] Wüst, Meuthen, and Durrer,[140] Klinkhardt,[235] Umino,[268] Lapp,[280] Jaeger and Rosenbohm,[416] Ahrens,[475] Grew,[488] Ewart,[561] and Moser.[574] The data of Ahrens, Ewart, Grew, and Lapp are in good agreement

FIG. 85.—The specific heat of nickel at elevated temperatures.

FIG. 86.—Analysis of the specific-heat curve.

for temperatures below the sharp maximum at the magnetic inversion. At higher temperatures the course of the curve is in doubt, although that shown, mostly on the basis of Ewart's data, agrees fairly well with the slope indicated by Moser's data.

An incomplete analysis of the specific-heat curve is attempted in Fig. 86. The observed c_P curve is, of course, a combination of those shown in Figs. 84 and 85. The Debye c_V curve, which approaches a limit of $3R$ cal. per g. atom (R is the gas constant) or 0.1016 cal. per g. for nickel, was computed on the assumption of a characteristic temperature of 400°K, as suggested by Stoner.[582] The dilatation correction was estimated by means of the thermodynamic relation

$$c_P - c_V = \frac{\alpha^2 v T}{J\beta}$$

where α is the coefficient of cubical expansion, v is specific volume, T is absolute temperature, J is the mechanical equivalent of heat, and β is compressibility. Estimation of compressibility at high temperatures is a hazardous process. However, there is some information on the change of modulus of elasticity with temperature, and it seems unlikely that Poisson's ratio undergoes any large change, consequently the estimated values are a little better than fantasies. Subtraction of the c_V and dilatation correction curves from the observed c_P curve yields that which is marked ($c_M + c_E$). Separation of this curve into its components is impossible to accomplish with certainty and is not attempted here. (Stoner made probably the best attempt.) However, the high-temperature value of c_E is indicated by the curve, because c_M evidently disappears in the neighborhood of 450°C. This means that the electronic specific heat of nickel at high temperatures has a constant value of about 0.020 cal. per g. The temperature at which it begins to decline is not clear. If the constant value persists at the temperature of magnetic inversion, the magnetic component is then $0.052 - 0.020 = 0.032$ cal. per g. Ferromagnetic theory predicts about 0.031 cal. per g. The agreement may be too good to be true.

65. Specific Heat of Iron-nickel Alloys.—There is little useful information on iron-nickel alloys. Most valuable, perhaps, are the data of Dumas,[72] who worked with alloys containing 28.3, 39.4, 54.6, 70.2, and 84.2 per cent nickel and a sample of nickel; these

are given in Fig. 87. Comparison of Dumas' data on nickel with those of others indicates something to be desired by way of accuracy. One significant fact emerges however, and that is that the relative height of the maximum at the magnetic inversion depends upon the temperature of the inversion; *i.e.*, the magnetic specific heat is maximum in the neighborhood of 70 per cent nickel, where the inversion temperature is greater than that

FIG. 87.—The specific heat of iron-nickel alloys at elevated temperatures.
(*Dumas.*[72])

of any other gamma-phase alloy. More accurate data are required to make a detailed analysis.

To facilitate comparison with the few data of other workers, Dumas' curves were extrapolated to 20°C., although this is difficult to accomplish with certainty, because of the rapid change of specific heat in this range of temperature. Results are shown in comparison with those of Brown,[68] Tilden,[54] Ingersoll and others,[152] and with selected values for alpha and gamma irons and for nickel, in Fig. 88. The Ingersoll data

are mean specific heats for the range 30 to 100°C. and are conse-
quently higher than the true 20°C. values.   It is interesting,
therefore, that Brown's 10 to 13°C. data are in substantial
agreement with those of Ingersoll.   The specimens of both
investigators were not very pure, and this may partly account for
the high values.   It is possible, however, that these data give a
correct qualitative picture; if so, it is to be concluded that the
specific heat of alpha iron undergoes little or no change upon
addition of nickel and that a maximum is attained in the two-

Fig. 88.—The specific heat of iron-nickel alloys.

phase region.   Similarly, it is to be concluded that the specific
heat of nickel is increased slightly by the addition of iron in the
gamma-phase region.

The only other data that could be found were reported by
Kawakami[233] as mean values interpolated on the assumption of
linear change between 150 and 350°C., but they do not appear to
be worthy of reproduction.

Accurate information on the specific heat of iron-nickel alloys
would be very useful for a searching analysis of the properties of
the system.   One investigation is known to be in progress, but
results are not yet available.

66. Thermal Conductivity of Iron-nickel Alloys.—The latest and most reliable source of information on the thermal conductivity of metals is a report of Shelton and Swanger.[467] Compositions of alloys of interest here are given in Table 16. Thermal-conductivity measurements were self-consistent to a high degree and . permitted interpolation to regular temperature

FIG. 89.—The thermal conductivity of iron-nickel alloys. (*Shelton and*

intervals without difficulty; these values are given in Fig. 89. To summarize these data (and others on metals and alloys containing no nickel), the following statements of Shelton and Swanger are reproduced:

For the pure metals, the irons and low-alloy steels, the thermal conductivities decrease with increase in temperature. The conductivities of the high-alloy steels and of the nickel alloys increase with tem-

perature.   In general, the thermal conductivities of all of the materials tested are linear functions of the temperature within the range within which measurements were made.   A noteworthy exception is nickel: a sharp change from a negative to a positive temperature coefficient occurs at the temperature of magnetic transformation.

For the ferrous alloys, an increase in the amount of alloying constituents in iron caused, in general, an increase in the temperature coefficient of thermal conductivity.   However, the many, and sometimes conflicting, factors concerned make it practically impossible to generalize concerning the quantitative relationship of thermal conductivity and total alloy content of ferrous metals.

TABLE 16.—COMPOSITION OF THERMAL-CONDUCTIVITY SPECIMENS*

Mark	Composition, per cent							
	Fe	Ni	Cr	C	Mn	P	S	Si
N_1	0.03	99.94	.....	0.005	....	.....	0.004	0.006
NS	0.60	99+	.....	.....	0.09	.....	0.014	
C_1	.....	.....	.....	0.02	0.03	0.042	0.005	
S_2	.....	1.37	0.46	0.35	0.56	0.015	0.020	0.02
N_6	56	34	10					
N_5	23	61	16					

* Shelton and Swanger.[467]

Earlier data on the thermal conductivity of nickel, obtained by Honda and Simidu[130] and by Schofield,[223] indicate minimum values somewhere between 300 and 500°C. and thus agree in trend with those of Shelton and Swanger, but they lack the self-consistency shown in Fig. 89.

Inspection of Shelton and Swanger's curves for the two grades of nickel indicates great sensitivity to impurity; this is consistent with the more or less parallel behavior of electric and thermal conductivities often observed.   A curve showing the variation of thermal conductivity with composition for a given temperature should then be roughly U-shaped, and Fig. 90 has been so drawn. The only data on any considerable number of iron-nickel alloys were reported by Honda[144] and by Ingersoll and his coworkers.[152]   These two sets of results are in fair agreement, but the unquestionably low values for iron and for nickel indicate that higher conductivities may be expected for high-purity materials— at least for those rich in iron or in nickel.   Other points shown

were reported by Benedicks, Bäckström, and Sederholm,[229] by Shelton and Swanger,[467] and by Cleaves and Thompson[520] (a suggested value for iron at room temperature). The curve was assumed to consist of two branches—one for alpha-phase alloys and the other for gamma-phase alloys—and the attempt was made to approximate room-temperature values. Whether or not this was accomplished remains to be seen. It is unfortunate that Shelton and Swanger's specimens did not include a few iron-nickel alloys.

Of the few data on complex alloys, those of Shelton and Swanger on two iron-nickel-chromium alloys seem to be the most

FIG. 90.—The thermal conductivity of iron-nickel alloys.

reliable. (They are included in Fig. 89; specimen N_5 contained 61 per cent nickel and 16 per cent chromium; specimen N_6 contained 34 per cent nickel and 10 per cent chromium.) In spite of marked difference in nickel content, there was small difference of thermal conductivity.

D. AUTHOR'S SUMMARY

1. The modulus of elasticity of alpha-phase iron-nickel alloys declines from about 30 million lb. per sq. in. for iron to about 22 million lb. per sq. in. at 30 per cent nickel. That for gamma-phase alloys increases—first rapidly, then slowly—from about 21 million lb. at 35 per cent nickel to about 30 million lb. for nickel.

2. There is no information on directly determined values of Poisson's ratio, and computed values are in doubt. Some evi-

dence exists, however, that indicates little change with composition, and a value of 0.3 is suggested.

3. A curve for the modulus of rigidity, computed from the selected values of modulus of elasticity and the suggested Poisson's ratio, is consistent with observed values.

4. Data from two sources on the bulk modulus are not in agreement; further measurements are needed.

5. The temperature coefficient of the modulus of elasticity at ordinary temperature of iron-nickel alloys is unusual because it is positive in sign for alloys containing approximately 28 to 44 per cent nickel. Iron-nickel alloys containing other elements, such as chromium, may have a negligible temperature coefficient at ordinary temperature. These alloys, called elinvars, now contain 31 to 33 per cent nickel, 4 to 5 per cent chromium, 1 to 3 per cent tungsten, and smaller amounts of manganese, silicon, and carbon.

6. Lattice constants of iron-nickel alloys are fairly well established for temperatures up to about 600°C. The variation of lattice dimensions with composition is unusual, but there is no adequate explanation as yet.

7. Observed specific volumes agree satisfactorily with limiting values computed from X-ray data. The unusual variation with composition of lattice dimensions of course exists also for this quantity.

8. Adequate specific-heat data on iron-nickel alloys are lacking, but, if available, should be very useful, for example in analysis of magnetic behavior.

9. The thermal conductivity of iron-nickel alloys in the vicinity of room temperature is fairly well established. The curve is roughly U-shaped and evidently consists of two branches—one for gamma-phase and one for alpha-phase alloys.

CHAPTER VI

THERMAL EXPANSION

Thermal Expansion of Iron-nickel Alloys—Thermal Expansion of Iron-nickel-cobalt Alloys—Explanations of Invar—Author's Summary

The thermal expansion of alloys of iron and nickel is very different from that of non-ferrous alloys in that there is marked deviation from rule-of-mixtures values. Adaptation of this phenomenon to useful purposes was chiefly the work of Guillaume[148] of the Bureau International des Poids et Mesures, who was interested in finding cheaper materials for metrology than the platinum-iridium alloy which was standard in 1889. Preliminary examination disclosed the fact that pure nickel possesses the desirable properties of resistance to oxidation, invariance with time, rigidity, and moderate expansibility; but the difficulty of obtaining sound bars of sufficient length deterred Guillaume from using it. In 1896, Guillaume found that a bar of 30 per cent nickel steel which was magnetic had a coefficient of expansion at ordinary temperature about two-thirds of that of platinum; "thus opened a promising line of investigation, which was eagerly pursued." The first step was determination of the trend of expansibility as a function of composition; this led to the discovery of the difference between reversible and irreversible alloys (page 32). Magnetic methods were used to detect transformations, since it was assumed that the cause of anomalous expansion of the preliminary alloys would affect also other properties. Determination of the expansion of reversible alloys established beyond doubt that the coefficient of expansion of iron-nickel alloys at ordinary temperature passes through a minimum in the vicinity of 36 per cent nickel. To alloys having coefficients of expansion in the neighborhood of the minimum value, Guillaume gave the name *invar* (from invariable), and by this name they have been known ever since. (Some manufacturers use the names *nilex, nilvar,* or *indilitans.*)

By selecting a suitable composition, materials become available which range in coefficient of expansion, over certain ranges of

135

temperature, from substantially zero to that of ordinary steel. Alloys of lowest expansion are used, for example, in the construction of wires and tapes for geodetic measurement and of meter bars. In horology, invar pendulums have replaced the compensated kind using mercury. An important use of invar is in the form of struts which compensate the relatively high expansion of aluminum-alloy pistons for internal-combustion engines. Much iron-nickel alloy is used in the form of "thermostatic bi-metal," which is the actuating material of one type of temperature controller. The 46 per cent nickel alloy has approximately the same coefficient of expansion as glass, consequently it was once used for lead-in seals of electric lamps; it has been replaced by a copper-coated alloy containing 42 per cent nickel. This alloy is also used for certain electric-refrigerator seals. In the radio industry, the 39 per cent nickel alloy is used in the manufacture of power tubes made of special low-expansion glass. The 56 per cent nickel alloy has approximately the coefficient of expansion of ordinary steel, but has the advantages of invariance of dimensions with time and higher resistance to corrosion, hence is useful in the construction of measuring devices for testing gages and machine parts. Thus, once discovered, it did not take long to find applications for the wide range of expansion characteristics offered by iron-nickel alloys.

The influence of impurities on the thermal expansion of iron-nickel alloys is of some importance, consequently available information on the matter is given. Other information given is on the expansion of iron-nickel alloys to which substantial additions of alloying elements have been made.

A. THERMAL EXPANSION OF IRON-NICKEL ALLOYS

A metallic body ordinarily expands when heated. If l_0 represents its length at a temperature t_0, and if l_1 represents its length at a temperature t_1, then the expansion accompanying a temperature change of $t_1 - t_0$ is clearly $l_1 - l_0$, or Δl. The expansion per unit length, $\Delta l/l_0$, may be called the expansivity. Empirically, the expansivity is given by a relation of the form

$$\Delta l/l_0 = at + bt^2 + \cdots \tag{1}$$

where a and b are empirical constants (mean coefficients of

expansion) and t is the temperature interval. In technology, powers higher than the first are often neglected.

The true, or instantaneous, coefficient of expansion is defined by

$$\alpha = \frac{1}{l_0}\frac{dl}{dt} \tag{2}$$

The value of dl/dt is obtained most easily by determining the slope of the $\Delta l/l_0\text{-}t$ curve at the point representing the required temperature.

FIG. 91.—Schematic expansion curve of an irreversible iron-nickel alloy.

67. Expansivity of Irreversible Alloys.—The expansion loop typical of irreversible alloys (which are discussed on pages 32 to 34) was discovered by Guillaume[23] and fully verified by Charpy and Grenet[46] and Chevenard.[110] By way of review, a schematic expansion curve of an irreversible alloy is given in Fig. 91. Upon heating from say 0°C., the alloy expands along EDF; at point F, alpha-gamma transformation begins; this continues along $FB'B$ and is complete at point B; further expansion proceeds along BA. Upon cooling from point A, contraction sets in and path AB is retraced. Gamma-alpha transformation does not set in upon reaching point B, however, because the extension

BC of path AB is followed. Transformation does set in upon reaching point C; this continues along CC'D and is complete at point D. Upon still further cooling, path DE is retraced. This cycle can be repeated indefinitely, provided that there is no drastic alteration of rate of temperature change.

If the cooling is halted at point C' and the specimen reheated, the expansion now follows path C'B'BA; or, if the original heating is halted at point B' and the specimen cooled, the change of length follows path B'C'DE. The slope of line AC is about 17×10^{-6}; this is the coefficient of expansion of gamma-phase alloy. The slope of line EF is about 11×10^{-6}; this is the

Fig. 92.—Schematic expansion curve typical of alloys containing about 40 per cent nickel.

coefficient of expansion of alpha-phase alloy. All intermediate values of the coefficient can be obtained by arresting the alpha ⇌ gamma transformation at a suitable point on the branches DC and FB.

68. Expansivity of Reversible Alloys.—It was discovered by Guillaume[23] that the expansivity of alloys of the invar type is altogether different from that of irreversible alloys. This may be illustrated by a schematic expansion curve typical of alloys containing about 40 per cent nickel (Fig. 92). Upon cooling from point F, the alloy contracts along path FE (which corresponds to AB of Fig. 91). This is the expansion curve of the non-ferromagnetic gamma phase. The change of slope which begins at point E does not indicate the beginning of gamma-

alpha transformation, as does point C of Fig. 91; it does mark the appearance of ferromagnetism. Rapid change of slope in the direction of decreasing contraction continues to point D. Further cooling along path DC is accompanied by small and nearly constant contraction. Rapid change of slope reappears along CBA, in the direction of increasing contraction. Upon reheating, these phenomena are retraced in reverse order.

Practically speaking, the CD portion of Fig. 92 is most important, because its slope determines the minimum coefficient of expansion and its length the useful temperature range of the alloy.

FIG. 93.—Variation with composition of the coefficient of expansion at 20°C. (70°F.) of alloys containing about 0.4 per cent manganese and 0.1 per cent carbon. (*Guillaume.*[23])

Guillaume's[23] first move in his investigation of iron-nickel alloys was to determine the variation of coefficient of expansion with nickel content. The results given in Fig. 93 are for alloys containing about 0.4 per cent manganese and 0.1 per cent carbon in the hot-rolled, air-cooled condition. Guillaume found that equation (1) applies sufficiently to iron-nickel alloys over the narrow temperature interval 0 to 38°C. (32 to 100°F.) even though all terms beyond the second degree are dropped. The true coefficient of expansion at temperature t is then

$$\alpha = a + 2bt$$

The coefficient b may be called the quadratic or curvature coefficient. Its variation with nickel content is given in Fig. 94, with temperature in Fig. 95. From the latter, Guillaume evolved

his "rule of corresponding states," on the observation that the
high positive values of b correspond to the temperature range

FIG. 94.—Variation with composition of the quadratic coefficient of expansion
of alloys containing about 0.4 per cent manganese and 0.1 per cent carbon.
(*Guillaume.*[23])

FIG. 95.—Schematic representation of expansivity and the coefficients of expan-
sion as a function of temperature.   (*Guillaume.*[23])

of rapid change of spontaneous magnetization.   The "rule" was
simply that at equivalent distances from the magnetic inversion

FIG. 96.—The thermal expansion of some iron-nickel alloys. (*Chevenard.*[110])

FIG. 97.—The coefficients of expansion of some iron-nickel alloys from the curves of Fig. 96. (*Chevenard.*[110])

different alloys would be in analogous states. Although the rule was admittedly inexact, Guillaume was able to infer correctly the behavior of alloys at temperatures beyond the limit of his apparatus; Chevenard's[110] later measurements were in complete agreement with Guillaume's prediction.

Fɪɢ. 98.--The coefficients of expansion of some high-nickel alloys. Numerals indicate nickel content. (*Chevenard.*[128])

Chevenard's measurements were on forged alloys containing up to 98 per cent nickel, less than 0.05 per cent carbon, and just enough manganese to permit mechanical working. To insure complete transformation, the specimens were cooled to low temperatures, some to −253°C. (−423°F.) in liquid hydrogen. This treatment caused no permanent change of length in alloys containing more than 35 per cent nickel.

As was stated on page 137, Chevenard succeeded in confirming experimentally the expansion loop of irreversible alloys. Alloys containing from 35 to 68 per cent nickel yielded expansion curves of the type illustrated by Fig. 92, some of which are reproduced in Fig. 96. It is to be noted that the expansion of the 35.4 per cent nickel alloy (invar) above 300°C. (570°F.) is very similar to that of ordinary steel. That low expansion of such alloys exists only over a limited temperature range is shown vividly by Fig. 97, in which the true coefficients of expansion of

FIG. 99.—The coefficient of expansion of nickel.

the alloys of Fig. 96 are given. From these results Chevenard concluded that the phenomenon of minimum expansion gradually disappears as alloy composition approaches 68 per cent nickel. This conclusion is supported by the data given in Fig. 98, which were also reported by Chevenard.[128] It is to be observed that the character of the coefficient curve changes somewhere between 66.8 and 77.2 per cent nickel.

69. Expansion of Iron Compared with That of Nickel.—It has been demonstrated (see, *e.g.*, Cleaves and Thompson,[520] page 160) that the coefficient of expansion of iron passes through a minimum at the magnetic-inversion temperature. The coeffi-

cient of expansion of nickel, however, passes through a maximum
at that temperature, as may be seen by inspection of Fig. 99.
This curve was constructed from data of Williams,[510] Owen and
Yates,[576] Schulze,[579] and Austin;* although not entirely trust-
worthy in all respects, there is absolutely no doubt about the
maximum.   Comparison with Fig. 98 shows that Chevenard's

Fig. 100.—Thermal expansion of some low-expansion iron-nickel alloys.
(Scott.[287])

curve for 99 per cent nickel is in good agreement.   It is reason-
able to expect with Chevenard, therefore, that, since the invar-
type alloys yield coefficient curves of the iron type, there is some
intermediate composition for which there is no anomalous
expansion.

70. Scott's Investigation.—Probably. the most complete data
on the expansion of invar-type alloys are those of Scott.[287]

* Private communication.

The alloys were prepared from electrolytic iron and electrolytic nickel, usually with the addition of about 1 per cent manganese. Measurements were made also on commercial alloys. The cobalt content of the laboratory alloys was less than 0.2 per cent, of the commercial alloys less than 1 per cent.

FIG. 101.—Thermal expansion of some low-expansion iron-nickel alloys. According to Table 17, page 149, alloy 1794 contained 42.8 per cent nickel.

Scott noted that the magnetic inversion is one limit of the range of low expansion; since the rate of expansion changes continuously through the region of magnetic inversion, it is difficult to determine a point characterizing the limit. Scott avoided the difficulty by taking the intersection of the minimum slope of the expansion curve with the slope of the curve just above the magnetic-inversion temperature; the temperature correspond-

FIG. 102.—Thermal expansion of some commercial iron-nickel alloys. (*Scott.*[287])

FIG. 103.—Expansion characteristics of iron-nickel alloys.

ing to the intersection is termed the "inflection temperature." The inflection temperatures for Scott's alloys are illustrated in Figs. 100 and 101 for the laboratory alloys, and in Fig. 102 for the commercial alloys. These temperatures, the minimum coefficients of expansion, and the temperature ranges of minimum coefficient are assembled in Fig. 103. It is to be seen that inflection temperature and minimum coefficient of expansion increase rapidly when the nickel content is increased from about 36 per cent. Coefficients of expansion are given in Figs. 104 to 106.

FIG. 104.—The coefficients of expansion of some iron-nickel alloys.

These curves were used to determine the temperature ranges over which the coefficient does not change by more than 0.5×10^{-6}. These and other data are collected in Table 17.

71. X-ray Determination of Thermal Expansion.—In a recent series of papers, Owen and Yates[604,605] and Owen, Yates, and Sully[607] gave expansion data on some high-purity iron-nickel alloys which had been determined by means of a high-temperature X-ray camera. Comparison of the coefficients of expansion determined from lattice-constant curves with those determined dilatometrically by other workers demonstrated that the overall rate of expansion of polycrystalline material is the same as that of the lattice of single crystals.

FIG. 105.—The coefficients of expansion of some iron-nickel alloys containing about 0.9 per cent manganese.   (*Scott.*[287])

FIG. 106.—The coefficients of expansion of some commercial iron-nickel alloys (No. 181, 42.8 per cent nickel; No. 182, 38.2 per cent nickel; No. 13, 37.2 per cent nickel; No. 17, 36.5 per cent nickel).   (*Scott.*[287])

A summary of results, given by Owen, Yates, and Sully,[607] is reproduced in Fig. 107. They show all curves to pass through points A and B because the corresponding alloys were found to have uniform rates of expansion.

72. Effect of Other Elements on the Thermal Expansion of Iron-nickel Alloys.—The effect of additions of carbon, manganese, copper, or chromium on the expansion of iron-nickel alloys was investigated by Guillaume.[148] His results are given in Figs. 108

TABLE 17.—EXPANSION CHARACTERISTICS OF SOME IRON-NICKEL ALLOYS*

Mark	Compo-sition, per cent		Inflection temper-ature		Minimum coefficient of expan-sion $\times$ 10^6, per		Temperature range of low coefficient			
							Minimum		Maximum	
	Ni	C	°C.	°F.	°C.	°F.	°C.	°F.	°C.	°F.
1700	31.36	0.03	50	120	7.0	3.9				
1791	33.31	0.03	125	255	1.3	0.7	−150	−240	−20	−5
1717	33.83	0.02	130	265	1.1	0.6	−150	−240	0	30
1793	35.89	0.02	190	375	1.2	0.7	−50	−60	70	160
1819	38.17	0.03	245	475	1.6	0.9	20	70	130	265
1863	40.17	0.01	310	590	2.4	1.3	70	160	210	410
1864	42.12	0.01	325	615	3.9	2.2	110	230	250	480
1794	42.76	0.01	375	705	5.5	3.1	110	230	280	535
1817	44.77	0.03	385	725	6.2	3.4	180	355	330	625
1718	47.09	0.01	420	790	7.3	4.1	150	300	370	700
10	50.19	0.00	500	930	9.6	5.3	160	320	420	790
13†	37.24	0.08	255	490	2.2	1.2	−10	14	130	265
17†	36.49	0.09	245	475	1.0	0.6	−10	14	130	265
182†	38.2	0.12	275	525	2.2	1.2	40	105	170	340
165†	43.10	0.12	365	690	5.4	3.0	150	300	300	570
181†	42.80	0.11	365	690	5.3	2.9	120	250	310	590

* Scott.[237]
† Commercial steels.

and 109; these curves show the displacement of the minimum of Fig. 93. Figure 108 shows that manganese and chromium increase the nickel content for minimum coefficient of expansion, whereas carbon and copper decrease it. Figure 109 shows that the value of the minimum coefficient was in every instance increased. The thermal expansion of five iron-nickel-copper alloys, containing a maximum of 33.3 per cent nickel and copper

up to 65 per cent, was determined by Kosting.[350]   Increased copper content caused the expansion curves to take the form characteristic of those for non-ferrous metals.   Copper is clearly not an element to add if a wide temperature range of low expansion is sought.

Fig. 107.—The coefficients of expansion of iron-nickel alloys from X-ray data. (*Owen, Yates, and Sully.*[607])

Fig. 108.—Displacement of nickel content for the minimum expansion by addition of a third element (manganese, chromium, copper, or carbon). (*Guillaume.*[148])

The foregoing data of Guillaume are for ordinary temperature; invar-type alloys are used over a range of temperatures, consequently Scott[287] studied the effect of the more usual impurities, manganese and silicon, by determining the expansion curves of alloys containing about 45 per cent nickel and various amounts of these elements (Fig. 110).   Their effect on inflection temperature and minimum coefficient was pronounced; 1 per cent man-

FIG. 109.—Change of the minimum coefficient of expansion by addition of a third element.

FIG. 110.—Effect of manganese and silicon on the thermal expansion of iron-nickel alloys.

ganese lowered the inflection temperature 20°C. (35°F.) and increased the minimum coefficient by 0.25×10^{-6}; 1 per cent silicon lowered the inflection temperature 30°C. (55°F.) but had no appreciable effect on the minimum coefficient.

Further data, on the effect of chromium, given by Chevenard,[160] are summarized in Figs. 111 and 112. To characterize the intensity of the abnormality of expansion, Chevenard

Fig. 111.—Components of expansion of a 40 per cent nickel iron-nickel alloy.

selected the magnitude at absolute zero (A_0 of Fig. 111) of the ferromagnetic component of expansion (page 179). Curve C of Fig. 111 represents the observed expansion of an alloy containing about 40 per cent nickel; curve c, extrapolated from the high-temperature portion of curve C, represents normal expansion; the differential curve Γ, extrapolated to absolute zero, permits evaluation of A_0. Data on alloys containing 0, 5, 10, and 15 per cent chromium, obtained in this way, are given in Fig.

Fig. 112.—Effect of chromium on the magnitude of anomalous expansion. (*Chevenard.*[160])

Fig. 113.—Coefficients of expansion of iron-nickel-chromium alloys. (*Chevenard.*[270])

112. It is to be seen that these data are in agreement with Guillaume's conclusion that chromium increases the minimum coefficient of expansion of alloys of the invar type. This is likewise true of Fig. 113, which shows the coefficient of expansion at 0°C. (30°F.) for alloys containing up to 15 per cent chromium, obtained by Chevenard.[270]

According to Hunter,[564] tungsten and molybdenum have an effect similar to that of manganese and chromium in that they

Fig. 114.—Effects of mechanical and thermal treatment on the expansion of an iron-nickel alloy containing 37.2 per cent nickel.   (Scott.[287])

increase the nickel content required for minimum coefficient of expansion.

The effect of cobalt on the thermal expansion of iron-nickel alloys is different from the effects of the elements discussed here, consequently the expansion of iron-nickel-cobalt alloys is described separately on pages 166ff.

73. Effect of Thermal and Mechanical Treatments.—It was discovered by Guillaume[51] that the coefficient of expansion of invar-type alloys in the vicinity of ordinary temperature can be changed markedly by thermal and mechanical treatments.

Annealing tends to increase the coefficient; rapid cooling by quenching tends to decrease its value. Cold working is even more effective in decreasing the coefficient; it is possible to produce even negative values. Alloys for which this is true can then be heated moderately, say at 100°C. (210°F.) for several hours, to reduce the coefficient to zero, or very nearly so.

The foregoing effects are demonstrated clearly by Scott's[287] data on an alloy containing 37.2 per cent nickel and 0.73 per cent manganese. The minimum coefficient of expansion was reduced from 2.2×10^{-6} to 0.7×10^{-6} by cold swaging the bar from ¼- to ⅛-in. diameter, and was then increased by annealing as is shown by Fig. 114. That cold work reduces the interval of minimum expansion is shown by the data of Table 18 taken from Fig. 114.

Similar results on the effect of thermal treatment on invar were found by Russell,[319] whose data are given in Table 19. Hunter[564] reported measurements on two heats for which the coefficient of expansion as received from the hot mill was 1.4×10^{-6}. Annealing followed by quenching reduced the coefficient to 0.5 to 0.8×10^{-6}; cold drawing further reduced it to 0.14 to 0.3×10^{-6}.

74. Dimensional Stability of Invar-type Alloys.—In discussing the expansion behavior of reversible alloys (page 138), certain secondary phenomena of practical importance were not considered. There may be, for example, transitory length changes

Table 18.—Effect of Annealing after Cold Swaging an Alloy Containing 37.2 Per Cent Nickel and 0.73 Per Cent Manganese*

Annealing temperature		Inflection temperature		Minimum coefficient per		Range of minimum coefficient	
°C.	°F.	°C.	°F.	°C.	°F.	°C.	°F.
25	75	235	455	0.7	0.4	0 to 100	30 to 210
400	750	240	465	1.4	0.8	0 to 110	30 to 230
600	1110	255	490	2.3	1.3	0 to 120	30 to 250
800	1470	250	480	2.1	1.2	0 to 140	30 to 285

* Scott.[287]

(aftereffects) following a temperature-change cycle, with the result that the expansion curve of the type illustrated by Fig. 92

(page 138) may not be retraced precisely upon subsequent heating and cooling. Factors that affect the length of a specimen at a given temperature—at least initially—are the temperature to which the specimen had been heated previously and the rate of approach to the final temperature. Assume a forged bar in a

TABLE 19.—EFFECT OF THERMAL TREATMENT ON THE COEFFICIENT OF EXPANSION OF A 36 PER CENT NICKEL ALLOY*

Number	Treatment	Temperature range		Mean coefficient of expansion $\times$ 10^6, per	
		°C.	°F.	°C.	°F.
1	As forged	17 to 100	64 to 210	1.66	0.9
		17 to 150	64 to 300	1.90	1.05
		17 to 200	64 to 390	2.32	1.3
		17 to 250	64 to 480	3.11	1.7
2	Quenched	18 to 100	65 to 210	0.64	0.35
		18 to 150	65 to 300	1.03	0.55
		18 to 200	65 to 390	1.47	0.8
		18 to 250	65 to 480	2.53	1.4
3	Quenched and tempered	15 to 100	59 to 210	1.02	0.55
		15 to 150	59 to 300	1.19	0.6
		15 to 200	59 to 390	1.57	0.85
		15 to 250	59 to 480	2.43	1.35
4	Cooled from 830°C. (1525°F.) in 19 hr.	15 to 100	59 to 210	2.01	1.1
		15 to 150	59 to 300	2.11	1.15
		15 to 200	59 to 390	2.37	1.3
		15 to 250	59 to 480	2.89	1.6

state corresponding to range *CD* of Fig. 92. If the bar has been brought to that state from a higher temperature, after the completion of normal contraction, it will slowly elongate with the passage of time. If the bar has been brought to that state from a lower temperature, after normal expansion is completed, it will slowly contract. The duration of this length change is always greater for the former case than for the latter. In any event,

the higher the temperature, the greater the rate of change of length. Guillaume[121] found that invar, brought to 100°C. (210°F.) immediately after forging, elongated at the rate of about 0.067 micron per m. per min.; if brought to this temperature after long storage at room temperature, it contracted at the rate of 0.8 to 0.9 micron per m. per min.

At 15°C. (60°F.), immediately after forging, the bar elongated at the rate of 0.07 to 0.08 micron per m. per day, but only 0.03 micron per m. per day after annealing at 40°C. (105°F.). After long storage at room temperature, contraction at 100°C. (210°F.)

Fig. 115.—Elongation of invar with time; upper curve, as forged; lower curve, cooled from 150 to 40°C. (300 to 105°F.) in 50 days. (*Guillaume, according to the National Bureau of Standards.*[183])

was complete in about 30 min., but contraction continued for several days at 40°C. (105°F.).

In addition to transitory changes of length which follow change of temperature, there are other changes of long duration at constant temperature. Guillaume[121] found that a bar of invar stored at constant temperature underwent elongation, at first rapidly, then more slowly, to approach a limit asymptotically; the elongation appeared to be an exponential function of time. To reduce these long-duration changes, Guillaume[129] invented a process of aging which consists of forging, then cooling through the range, for example, 100°C. (210°F.) to ordinary temperature, over a period of 2 to 3 months. Some of his data on the effect of aging treatment on forged bars of invar are reproduced in

TABLE 20.—EFFECT OF AGING ON HOT-FORGED BARS OF INVAR*

Nickel, per cent	Treatment	Elongation microns per m.	Coefficient of expansion at 20°C. (70°F.), $\alpha \times 10^6$
35.2	Hot forged...................		1.27
	4536 days at room temperature.	38	1.32
35.5	Hot forged...................		1.21
	Skin removed; 150 hr. at 100°C. (210°F.), 4820 days at room temperature......................	65	1.32
35.5	Hot forged...................		1.18
	Skin removed; 40 hr. at 150°C. (300°F.), cooled to 40°C. (105°F.) in 50 days; 4802 days at room temperature......................		1.31
35.5	Hot forged; 55 hr. at 100°C. (210°F.); 150 hr. at 60°C. (140°F.)..........		1.67
	62 hr. at 100°C. (210°F.); cooled to 25°C. (75°F.) in 73 days; 4015 days at room temperature..............	34	1.73
35.6	Quenched; 55 hr. at 100°C. (210°F.); 187 hr. at 60°C. (140°F.)..........		1.36
	4564 hr. at room temperature.......	26	1.42
35.5	Quenched; 55 hr. at 100°C. (210°F.); 189 hr. at 60°C. (140°F.).......... 479 hr. at 60°C. (140°F.); 856 hr. at 40°C. (105°F.); 690 days at room		1.28
	temperature; planed to H-section..		1.31
	4145 days at room temperature.....		1.32
35.5	Hot forged; 66 hr. at 100°C. (210°F.). 739 hr. at 60°C. (140°F.); cooled to 25°C. (75°F.) in 102 days; planed to H-section; 320 days at room temperature........................		1.30
			1.35
43.0	Hot forged.......................		7.33
	108 hr. at 100°C. (210°F.); 4496 days at room temperature..............		7.47

* Guillaume.[121]

FIG. 116.—Elongation of invar with time after cooling from 100 to 25°C. (210 to 75°F.) over a period of 3 months. (*Guillaume and Benoît, according to the National Bureau of Standards.*[183])

FIG. 117.—Influence of carbon on the dimensional stability of iron-nickel alloys.

Table 20 and Figs. 115 and 116. The upper curve of Fig. 115 represents the elongation, during a 4500-day period, of a bar of invar in the as-forged condition; the lower curve is for a similar bar previously heated to 150°C. (300°F.), then cooled to 40°C. (105°F.) in 50 days. The data of Table 20 indicate that the coefficient of expansion is increased in value somewhat by the aging treatment, but that, once aging is completed, the coefficient remains constant.

FIG. 118.—Coefficient of expansion at ordinary temperature of iron-nickel alloys.

According to Guillaume,[147] the cause of dimensional instability of invar-type alloys is the presence of carbon. Actual measurements are summarized in Fig. 117, which shows the change of length in microns per meter of bars of various nickel and carbon contents. The change of sign at about 43 per cent nickel is in agreement with practical observations.

The matter of stability has been discussed extensively by Guillaume;[254] further, the *National Bureau of Standards Circular* 58[183] contains an excellent review of the subject, consequently this brief outline seems adequate for most purposes.

75. Summary of Coefficients of Expansion.—As a working summary of coefficients of expansion, data taken from the sum-

mary of French and Sands,[483] which in turn was based on Chevenard's measurements (page 141), are given in Tables 21 and 22.

TABLE 21.—MEAN COEFFICIENTS OF EXPANSION OF IRON-NICKEL ALLOYS FOR VARIOUS TEMPERATURE RANGES*

Nickel, per cent	Mean coefficient of expansion $\times 10^6$, per °C., for								
	-130 to $-20°C.$	-20 to $95°C.$	95 to $200°C.$	200 to $315°C.$	315 to $425°C.$	425 to $540°C.$	540 to $650°C.$	650 to $760°C.$	760 to $870°C.$
30	6.2	11.2	15.6	17.4	18.1	18.5	18.9	19.1	19.5
35	1.4	1.3	3.3	12.3	16.0	17.3	18.0	18.6	19.0
37.5	3.2	2.3	2.7	7.2	14.7	16.7	17.6	18.3	18.9
40	4.9	4.1	3.8	4.8	12.7	15.8	17.2	18.0	18.8
45	8.1	8.2	7.6	7.2	8.0	14.5	16.4	17.5	18.4
50	9.6	10.0	10.0	10.0	10.1	13.1	15.8	17.0	18.1
55	10.4	11.1	11.5	11.7	11.8	12.1	15.3	16.8	17.8
60	10.6	11.6	12.3	12.8	13.2	13.6	15.2	16.7	17.8
65	10.6	11.8	12.7	13.5	14.2	14.7	15.3	16.8	17.8
70	10.7	12.0	13.0	13.7	14.7	15.4	16.1	17.1	17.9
75	10.7	12.2	13.1	14.1	15.1	16.0	16.7	17.2	18.0
80	10.7	12.3	13.3	14.3	15.5	16.6	17.0	17.5	18.1
85	10.8	12.4	13.5	14.6	15.8	17.1	17.0	17.5	18.1
90	10.9	12.6	13.8	14.9	16.2	16.7	17.0	17.6	18.3
95	11.2	12.8	14.1	15.3	16.6	16.7	17.1	17.9	18.6
100	11.3	13.0	14.4	15.8	16.5	16.9	17.5	18.2	18.9

* French and Sands.[483]   These data were taken from Chevenard's curves (page 141).

76. Other Data.—Some more or less scattered data on the thermal expansion of iron-nickel alloys and nickel steels are collected in this section. Some of them are plotted in Fig. 118. Of historical interest is LeChatelier's[17] value of 11.9×10^{-6} for a 25 per cent nickel alloy at ordinary temperature. Values obtained at the National Physical Laboratory, quoted by Kaye,[95] do not diverge markedly from the curve. Werner[107] gave expansivities to 300°C. (570°F.) for alloys containing 5, 25, and 33 per cent nickel. Mean coefficients of expansion at 40 to 100°C. (105 to 210°F.) were obtained by Honda and Ôkubô.[198]   Mean coefficients reported by Goerens[197] are given in Table 23. Blomqvist[230] reported mean coefficients at 20 to 100°C. (70 to 210°F.) for two pairs

TABLE 22.—MEAN COEFFICIENTS OF EXPANSION OF IRON-NICKEL ALLOYS
FOR VARIOUS TEMPERATURE RANGES*

Nickel, per cent	Mean coefficient of expansion $\times 10^6$, per °F., for								
	−200 to 0 °F.	0 to 200 °F.	200 to 400 °F.	400 to 600 °F.	600 to 800 °F.	800 to 1000 °F.	1000 to 1200 °F.	1200 to 1400 °F.	1400 to 1600 °F.
30	3.5	6.3	8.7	9.7	10.1	10.3	10.5	10.7	10.8
35	0.8	0.7	1.8	6.8	8.9	9.6	10.0	10.3	10.6
37.5	1.8	1.3	1.5	4.0	8.2	9.3	9.8	10.2	10.5
40	2.7	2.3	2.1	2.7	7.1	8.9	9.6	10.0	10.4
45	4.5	4.6	4.2	4.0	4.5	8.1	9.1	9.7	10.2
50	5.4	5.6	5.6	5.6	5.6	7.3	8.8	9.5	10.0
55	5.8	6.2	6.4	6.5	6.6	6.6	8.5	9.3	9.9
60	5.9	6.4	6.8	7.1	7.3	7.6	8.4	9.3	9.9
65	5.9	6.5	7.1	7.5	7.9	8.2	8.5	9.4	9.9
70	5.9.	6.7	7.2	7.7	8.2	8.6	8.9	9.5	10.0
75	6.0	6.8	7.3	7.8	8.4	8.9	9.3	9.6	10.0
80	6.0	6.8	7.4	8.0	8.6	9.2	9.4	9.7	10.0
85	6.0	6.9	7.5	8.1	8.8	9.5	9.5	9.7	10.1
90	6.1	7.0	7.6	8.3	9.0	9.3	9.4	9.8	10.2
95	6.2	7.1	7.8	8.5	9.2	9.3	9.5	9.9	10.4
100	6.3	7.2	8.0	8.8	9.2	9.4	9.8	10.1	10.5

* French and Sands.[483]   These data were taken from Chevenard's curves (page 141).

of alloys containing 35.5 and 38 per cent nickel, respectively, after several treatments; these values are consistent with similar data.   Schulze[266] obtained mean coefficients at 20 to 100°C. (70 to 210°F.) for a series of alloys; these are included in Fig. 118. Stäblein[435] confirmed the low coefficient of expansion at ordinary temperature of 36 per cent nickel alloys on one prepared from carbonyl materials.   Broniewski and Smolinski[443] gave the coefficient of expansion at 0°C. (30°F.) as a function of nickel content for alloys prepared from electrolytic iron and electrolytic nickel; their curve is similar to that of Fig. 118 but is too small for precise comparison.

Among the data on nickel steels is the value of 11.6 $\times$ 10^{-6} at 50°C. (120°F.) for a 3.5 per cent nickel, 0.59 per cent carbon alloy obtained by Ôkôchi, Majima, and Sato.[139]   Maurer and Schmidt[164] gave mean coefficients at 20 to 450°C. (70 to 840°F.) for nine steels; they are consistent with corresponding data from

TABLE 23.—COEFFICIENTS OF EXPANSION OF IRON-NICKEL ALLOYS*

Nickel, per cent	Mean coefficient of expansion × 10⁶,† 0°C. to									
	100°C.	200°C.	300°C.	400°C.	500°C.	600°C.	700°C.	800°C.	900°C.	1000°C.
30	8.8	12.5	14.1	15.0	15.6	15.8	16.1	16.6	17.0	17.4
36	2.1	3.2	6.1	8.6	10.1	11.2	12.1	12.8	13.4	14.0
44	6.6	6.5	6.4	6.4	8.1	9.3	10.6	11.6	12.5	13.3

Nickel, per cent	Coefficient of expansion × 10⁶,† at										
	0	100°C.	200°C.	300°C.	400°C.	500°C.	600°C.	700°C.	800°C.	900°C.	1000°C.
30	4.0	13.4	17.0	17.5	17.8	17.6	17.2	19.8	19.9	21.0	21.6
36	1.5	3.0	7	15	16	17	17	18	18	18	18
44	6.6	6.3	6	5	10	16	17	18	18	19	19

* Goerens.[197]
† Divide by 1.8 to convert to per degree Fahrenheit.

other sources. Often quoted are the mean coefficients obtained by Souder and Hidnert;[180] these are given in Table 24. Merz[311] reported expansivities of a series of steels containing up to 15 per cent nickel.

TABLE 24.—THERMAL EXPANSION OF SOME NICKEL STEELS*

Composition, per cent					Mean coefficient of expansion × 10⁶, per °C., † for the temperature ranges									
C	Mn	Si	Cr	Ni	25 to 100°C.	100 to 200°C.	200 to 300°C.	300 to 400°C.	400 to 500°C.	500 to 600°C.	600 to 700°C.	25 to 300°C.	300 to 600°C.	25 to 600°C.
0.17	0.01	0.135	2.50	3.94‡	10.8	11.7	13.5	14.0	14.5	14.4	....	12.1	14.3	13.3
0.41	1.11	0.115	....	2.00	11.6	11.9	14.0	16.2	15.7	16.5	16.4	12.6	16.1	14.4
0.33	0.78	0.094	....	3.59	10.9	11.5	13.6	15.2	15.1	15.7	....	12.1	15.3	13.8
0.38	1.17	0.10	....	0.81	11.2	12.7	14.3	15.2	16.2	16.7	16.4	12.9	16.1	14.5
0.39	1.21	1.04	....	3.67	11.6	12.0	13.2	14.2	15.2	15.6	....	12.3	15.0	13.7
0.20	1.10	.....	0.5	0.5	12.3	12.9	14.2	15.9	16.2	16.5	16.8	13.2	16.5	14.9
0.14	....	.....	....	34.52	3.7	8.4	14.1	16.6	18.4	18.8	19.1	9.2	18.2	13.6

* Souder and Hidnert.[180]
† Divide by 1.8 to convert to per degree Fahrenheit.
‡ 0.39 per cent vanadium.

Maurer and Schmidt[164] found five steels containing 2 to 4 per cent nickel and 0.3 to 1.5 per cent chromium to have mean coefficients at 20 to 450°C. (70 to 840°F.) ranging from 12.5 to 13.5 × 10⁻⁶; *i.e.*, slightly smaller than that of iron. Determinations on alloys containing substantial percentages of nickel and chromium, by Goerens,[197] are given in Table 25. Mathews'[218] data on nickel-chromium steels are reproduced in Table 26. Others on nickel-chromium steels were given by Merz[311] and by

TABLE 25.—COEFFICIENTS OF EXPANSION OF IRON-NICKEL-CHROMIUM ALLOYS*

Composition, per cent		Mean coefficient of expansion × 10⁶,† 0°C. to									
Ni	Cr	100°C.	200°C.	300°C.	400°C.	500°C.	600°C.	700°C.	800°C.	900°C.	1000°C.
7	20	16.6	17.0	17.2	17.5	17.8	18.2	18.6	18.9	19.3	19.8
82	18	13.9	14.7	15.0	15.2	15.3	15.6	15.9	16.4	17.0	17.5
60	10	11.5	12.3	12.8	13.4	13.9	14.4	15.0	15.5	15.9	16.4

Composition, per cent		Coefficient of expansion × 10⁶,† at										
Ni	Cr	0°C.	100°C.	200°C.	300°C.	400°C.	500°C.	600°C.	800°C.	900°C.	1000°C.
7	20	15.4	17.3	17.6	17.9	18.9	19.8	20.3	22.0	23.5	24.9
82	18	12.4	15.0	15.6	15.7	15.8	16.2	17.3	20.8	22.3	22.4
60	10	10.6	12.2	13.4	14.4	15.5	16.6	17.6	19.3	20.1	20.7

* Goerens.[197]
† Divide by 1.8 to convert to per degree Fahrenheit.

Among the data on miscellaneous materials containing nickel is Field's[298] value of 10.7 × 10⁻⁶ at ordinary temperature for an alloy containing essentially 20 per cent iron, 20 per cent molybdenum, and the remainder nickel. Hall[381] found a mean coefficient at 20 to 100°C. (70 to 210°F.) of 18.7 × 10⁻⁶ for steels containing about 12 per cent manganese, 3 to 5 per cent nickel, and less than 1 per cent carbon. For a similar temperature range, Page and Partridge[357] found a value of 15.4 × 10⁻⁶ for a steel containing 0.45 per cent carbon, 9.33 per cent chro-

TABLE 26.—THERMAL EXPANSION OF SOME HIGH-ALLOY STEELS*

Composition, per cent					Treatment†	Mean coefficient of expansion $\times 10^6$, per °C.,‡ for the temperature ranges		
C	Cr	Ni	Si	Mn		20 to 200°C.	20 to 400°C.	20 to 600°C.
0.33	24.58	.....	0.63	0.30	N	16.4	17.2	17.6
					Q	16.5	17.2	17.7
0.32	20.73	7.04	0.65	0.27	N	10.3	11.0	11.4
					Q	11.7	12.4	12.2
0.39	15.35	15.60	2.26	0.82	N	16.3	17.2	17.6
					Q	16.4	17.5	17.8
0.41	7.29	22.60	1.84	0.80	N	17.6	18.0	18.2
					Q	17.7	18.1	18.2
0.43	.....	28.28	0.25	0.73	N	13.8	16.1	16.3
					Q	13.8	16.1	16.5

* Mathews.[213]
† N = normalized; Q = quenched.
‡ Divide by 1.8 to convert to per degree Fahrenheit.

mium, 9.66 per cent nickel, and 1.96 per cent tungsten, and a value of 17.9×10^{-6} for a steel containing 0.52 per cent carbon, 11.16 per cent chromium, 13.0 per cent nickel, and 2.28 per cent tungsten; the steels were respectively oil quenched and air cooled.

Data obtained by Bolton and Bornstein[375] indicate that the coefficient of expansion of ordinary cast iron is not affected appreciably by the addition of 1.5 per cent nickel, although Boegehold[332] stated that that of a cylinder iron was reduced about 0.5×10^{-6} by the addition of 1.4 per cent nickel. The cast iron used for cylinder liners has a coefficient of expansion of about 18×10^{-6}; representative compositions, according to Jardine[345] and to Vanick Merica,[366] are 2.8 to 3 per cent carbon and at least 12.5 per cent nickel, 1.5 per cent chromium, and 5 per cent copper or 14 per cent nickel, 2 per cent chromium, and 6 per cent copper. Norbury and Morgan[425] found a mean coefficient of expansion of 18×10^{-6} for an austenitic cast iron containing 1.8 per cent carbon, 18 per cent nickel, 2 per cent chromium, 6 per cent silicon, and 1 per cent manganese; this value could be reduced to 14×10^{-6} by heat treatment.

Extensive data on the mean coefficient of expansion of nickel cast irons given by Wood[550] are reproduced in Table 27.

TABLE 27.—COEFFICIENTS OF EXPANSION OF SOME NICKEL CAST IRONS*

Composition, per cent						Mean coefficient of expansion $\times 10^6$, per °C., from 10°C.(50°F.) to						
						95°C. (200°F.)	150°C. (300°F.)	205°C. (400°F.)	260°C. (500°F.)	315°C. (600°F.)	370°C. (700°F.)	425°C. (800°F.)
C	Si	Mn	Ni	Cr	Cu							
3.15	2.16	0.42	.....	.....	.....	12.0	12.2	12.8	13.0	13.3	13.4	13.5
2.98	1.23	0.50‡	2.24	.....	.....	11.8	12.0	12.2	12.4	12.6	12.8	12.8
2.84	0.87	0.44	3.30	.....	.....	11.3	11.5	12.0	12.4	13.0	13.2	13.4
2.84‡	1.32	0.44‡	3.30‡	.....	.....	12.5	12.7	12.8	13.0	13.2	13.4	13.5
2.84‡	1.89	0.44‡	3.30‡	.....	.....	11.9	12.4	12.8	13.1	13.4	13.5	13.6
2.98‡	1.23‡	0.52	7.38	.....	.....	13.0	13.0	13.3	13.6	13.8	14.2	13.4
2.98‡	1.23‡	0.50‡	12.58	.....	.....	17.0	17.6	17.7	17.8	17.8	17.7	
2.98‡	1.23‡	0.50‡	20.56	1.61	.....	17.1	18.3	18.7	18.6	18.6	18.5	
3.15‡	1.75‡	1.00‡	13.96	2.13	6.00‡	18.5	19.2	19.3	19.2	19.2	19.2	
2.36	1.36	1.00‡	25.74	1.96	.....	12.5	14.4	15.5	16.0	16.4	16.6	
2.46	1.55	0.90	29.20	.....	.....	7.7	9.1	10.7	11.8	12.7	13.3	13.7
2.57	1.60	1.20	29.56	1.22	.....	7.4	8.9	10.2	11.3	12.3	12.9	13.4
2.71	1.59	0.93	30.96	2.64	.....	6.1	7.8	9.4	10.6	11.5	12.3	13.2
2.57	1.54	1.16	31.60	1.21	.....	6.5	7.7	8.9	10.3	11.3	12.1	12.7
2.50	1.27	1.00‡	34.50	3.59	.....	5.6	6.3	7.2	8.1	9.1	10.0	10.7
2.50‡	1.25‡	1.00‡	34.70	2.60	.....	4.1	5.2	6.3	7.6	8.4	6.9	10.8
2.25	1.65	1.80	43.68	3.21	.....	8.6	9.1	9.6	9.9	10.1	10.5	11.1
2.35	1.46	0.97	44.80	3.97	.....	8.6	8.9	9.2	9.5	9.7	10.4	10.8
2.46	1.40	0.94	46.45	3.93	.....	8.3	8.6	9.1	9.6	10.0	10.2	10.8
2.13	1.36	0.27	49.96	.....	.....	8.0	8.9	9.6	9.8	9.8	10.0	10.4
1.90‡	1.40‡	1.00‡	60.00‡	4.00‡	.....	12.8	13.3	13.5	13.7	13.6	13.7	14.1
1.70‡	1.40‡	1.00‡	70.00‡	4.00‡	.....	12.8	13.5	13.9	14.0	14.3	14.4	14.6
2.60	1.00‡	1.00‡	20.38	2.47	9.08	13.9	15.5	16.1	16.5	16.6	16.8	
2.27	1.53	0.96	30.82	4.19	15.10	8.6	9.3	9.9	10.5	11.1	11.7	12.3
2.15	1.46	1.01	34.84	4.03	17.03	10.0	10.7	10.9	11.2	11.6	11.9	12.2
2.95	0.90	0.40‡	4.86	1.55	.....	7.8	8.7	9.8	10.7	11.3	11.9	12.3
2.85‡	1.50‡	1.00‡	10.70‡	2.00‡	4.30‡	17.4	18.1	18.7	18.8	19.0	19.1	
2.00‡	1.50‡	1.00‡	28.20‡	4.00‡	11.30‡	8.4	9.4	10.4	11.3	12.0	12.7	

† Divide by 1.8 to convert to per degree Fahrenheit.
‡ Approximately.

B. THERMAL EXPANSION OF IRON-NICKEL-COBALT ALLOYS

Even though invar can be made with a zero coefficient of expansion at ordinary temperature, the temperature range of low coefficient does not extend much beyond 100°C. (210°F.). Guillaume, as was shown in the earlier portions of this chapter, found that low expansion at higher temperatures was attained by increasing the nickel content, although this increased the minimum expansion. Introduction of other elements in the hope that

low expansion could be retained by alloying did not produce encouraging results. Cobalt, however, was not one of the elements tried by Guillaume; this addition, according to Scott,[364] was first made by P. H. Brace. The result was such that investigation of the expansion characteristics was undertaken by Scott; another investigation, discussed later, was in progress at about the same time.

Fɪɢ. 119.—Thermal expansion of some iron-nickel-cobalt alloys. (*Scott.*[364])

77. Scott's Investigation.—Scott's[364] alloys were prepared in a high-frequency furnace from electrolytic iron, electrolytic nickel, and other elements in a high-frequency furnace. The 2-in. square ingots were forged to ⅜-in. bars, then rolled or swaged to ¼-in. rods. Expansion measurements were made after annealing. Since the concern was with low-expansion alloys, only those in the gamma-phase range at ordinary temperature

were made.   Compositions are given in columns 2, 3, and 4 of
Table 28.

One series of alloys contained 32 per cent nickel and cobalt
varying from 6 to about 19 per cent; expansion curves on heating
for these alloys are given in Figs. 119 and 120.   As a qualitative

Mark	%Ni	%Co	%Mn
1989	31.6	18.6	0.78
1988	31.6	16.7	0.83
1784	31.9	14.2	0.85
2034	32.7	11.0	0.62

Fɪɢ. 120.—Thermal expansion of some iron-nickel-cobalt alloys.

basis of comparison, two of these curves as compared with a
cobalt-free alloy, for which the range of low expansion is about the
same, are given in Fig. 121.   It appears that cobalt lowers
the expansivity for a given inflection temperature and raises the
inflection temperature for a given minimum expansivity.   As a
general basis of comparison, Scott selected the numerical values
of inflection point and minimum coefficient of expansion; these

are given in Table 28 in the group marked "constant nickel, variable cobalt series." Comparison of the inflection temperatures with those given on page 149 for cobalt-free alloys shows that nickel-plus-cobalt content is approximately equivalent to nickel content. Cobalt evidently has about the same quantitative effect as nickel on the inflection temperature. It is to be noted also that the minimum coefficient of expansion was lowered by substitution of nickel by cobalt.

%Ni	% Co
○ 43.1	0
◑ 32.7	11.0
● 31.6	16.7

Fig. 121.—Thermal expansion of some iron-nickel-cobalt alloys.

Determination of optimum concentrations of nickel and cobalt would be simpler if no other elements were present. Chief among the other elements almost invariably present are carbon and manganese; their influence can be inferred from Figs. 122 and 123 and from series 1 and 5 of Table 28. Both increase the mean and minimum coefficients of expansion; manganese decreases the inflection temperature, and carbon appears to increase it slightly.

To complete the information, Scott prepared groups of alloys for which compositions and expansion behavior are given in the

TABLE 28.—EXPANSION PROPERTIES OF IRON-NICKEL-COBALT ALLOYS*

Mark	Composition, per cent				Inflection temperature		Coefficient of expansion			
	Ni	Co	Mn	C			Minimum, per		Mean,† per	
					°C.	°F.	°C.	°F.	°C.	°F.
Variable manganese series										
1912	45.2	<1.0	0.53	....	420	790	6.1	3.4	7.0	3.9
1913	45.4	<1.0	1.96	....	390	735	6.6	3.7	7.3	4.1
1914	45.4	<1.0	5.03	....	325	615	7.4	4.1	8.2	4.6
2123	29.8	15.5	0.22	....	415	780	3.3	1.8	4.3	2.4
2125	28.0	17.4	0.64	....	400	750	3.1	1.7	4.1	2.3
Constant nickel, variable cobalt series										
1782	31.8	6.0	0.84	....	240	465	0.9	0.5	2.4	1.3
2031	32.4	8.2	0.66	....	295	565	1.7	0.9	2.6	1.4
1783	31.9	9.8	0.79	....	335	635	2.4	1.3	3.0	1.7
2034	32.7	11.0	0.62	....	375	705	3.0	1.7	4.0	2.2
1784	31.9	14.2	0.85	....	425	790	4.3	2.4	5.4	3.0
1987	31.8	16.0	0.65	....	450	840	5.0	2.8	6.0	3.3
1988	31.6	16.7	0.83	....	450	840	5.4	3.0	6.3	3.5
1989	31.6	18.6	0.78	....	495	925	6.2	3.4	7.4	4.1
Constant nickel-plus-cobalt, variable cobalt series										
1988	31.6	16.7	0.83	....	455	850	5.5	3.1	6.3	3.5
2091	28.0	20.7	0.67	....	460	860	4.7	2.6	5.8	3.2
2092	26.4	23.3	0.74	....	480	895	5.1	2.8	6.2	3.4
2114	25.1	23.4	0.68	....	465	870	4.2	2.3	5.5	3.1
2089	24.8	23.9	3.52	....	390	735	5.3	2.9	6.2	3.4
Variable nickel-plus-cobalt, maximum cobalt series										
1782	31.8	6.0	0.84	....	240	465	0.9	0.5	2.4	1.3
2125	28.0	17.4	0.64	....	400	750	3.1	1.7	4.1	2.3
2091	28.0	20.7	0.67	....	460	860	4.7	2.6	5.8	3.2
2092	26.4	23.3	0.74	....	480	895	5.1	2.8	6.2	3.4
2127	23.6	29.6	0.81	....	500	930	6.6	3.7	7.7	4.3
2118	19.8	38.2	0.91	....	620	1145	8.0	4.4	9.3	5.2
Variable carbon series										
2114	25.1	23.4	0.66	0.03	465	870	4.2	2.3	5.5	3.1
2147	24.1	24.0	0.56	0.02	460	860	3.9	2.2	5.4	3.0
2148	24.1	24.0	0.52	0.11	470	880	4.2	2.3	5.6	3.1
2149	24.1	24.0	0.57	0.19	470	880	4.3	2.4	5.8	3.2
2150	24.1	24.0	0.61	0.33	465	870	4.3	2.4	5.9	3.3

* Scott,[364]
† From 0°C. (30°F.) to the inflection point.

"constant nickel-plus-cobalt, variable cobalt series" and the "variable nickel-plus-cobalt, maximum cobalt series" of Table 28; results are given in Figs. 124 and 125.

Analysis of the foregoing data led Scott to express them in the form of some empiric equations; in them, θ is written for inflection temperature, X for nickel content, Y for cobalt con-

FIG. 122.—Effect of carbon content on alloys containing various amounts of carbon. (*Scott.*[364])

tent, Z for manganese content, and W for carbon content. The inflection temperature is then given by

$$\theta = 19.5(X + Y) - 22Z - (0W) - 465$$

The cobalt and nickel contents that hold the gamma-alpha transformation in the neighborhood of $-100°C$., when the inflection temperature falls between 200 and 600°C., are

$$Y = 0.0795\theta + 4.8Z + 19W - 18.1$$
$$X = 41.9 - 0.0282\theta - 37Z - 19W$$

The minimum coefficient of expansion for these compositions is given by

$$\alpha \times 10^6 = 0.024\theta + 0.38Z - 1.2W - 6.65$$

This equation shows that manganese is detrimental and that carbon is beneficial in low-expansion alloys containing the maximum permissible cobalt content.

Fɪɢ. 123.—Thermal expansion of iron-nickel-cobalt alloys containing manganese.

78. Masumoto's Investigation.—Mean coefficients of expansion for the 30 to 100°C. (85 to 210°F.) range of nearly 70 iron-nickel-cobalt alloys were reported by Masumoto,[391] whose work was evidently in progress at about the same time as that of Scott. These data are shown in projection in Fig. 126; they indicate that the mean coefficient, for the temperature range considered, of low-expansion iron-nickel alloys is diminished by addition of cobalt. For this reason, Masumoto subjected the

composition region of low expansion to further investigation. Measurements were made from liquid-air temperature to about 350°C. (660°F.); these are given in Fig. 127 (compositions are given in Table 29). The abrupt expansion at low temperature indicated for all alloys containing less than 33.5 per cent nickel was a consequence of gamma-alpha transformation as the alloys were cooled in liquid air.

FIG. 124.—Thermal expansion of alloys of constant nickel-plus-cobalt and variable cobalt contents. (*Scott.*[384])

Examination of Fig. 127 shows that the coefficient of expansion of invar-type alloys at ordinary temperature can be reduced by substitution by cobalt of some of the nickel. Coefficients at 20°C. (70°F.) determined from these curves are given in Table 29.

Masumoto named his low-expansion iron-nickel-cobalt alloys "super-invars"; since their expansion behavior was determined in the annealed condition, he argued that they had also the advantage of great dimensional stability.

TABLE 29.—COEFFICIENTS OF EXPANSION OF SOME IRON-NICKEL-COBALT
ALLOYS*

Number	Composition, per cent			Coefficient of expansion $\times 10^6$ at 20°C. (70°F.), per	
	Ni	Co	Mn	°C.	°F.
1	36.5	. . .	. . . .	1.2	0.7
2	34.0	3.5	. . . .	0.3	0.2
3	32.5	4.0	. . . .	0.0	0.0
4	33.0	4.0	. . . .	0.4	0.2
5	33.5	4.0	. . . .	0.5	0.3
6	31.5	5.0	. . . .	0.0	0.0
7	32.5	5.0	. . . .	0.5	0.3
8	30.5	6.0	. . . .	0.0	0.0
9	31.5	6.0	. . .ʴ.	0.1	0.0(6)
10	31.0	5.0	0.35	0.1	0.0(6)
11	31.0	6.0	0.38	0.0	0.0

* Masumoto.[391]

C. EXPLANATIONS OF INVAR

The discovery that the thermal expansion of certain alloys of iron and nickel deviates markedly from that which would be predicted by the rule of mixtures was soon followed by attempts to explain this phenomenon. Since the composition of invar lies near that of hypothetical compound Fe_2Ni, this compound was the basis of several explanations, *e.g.*, those of Guillaume[27] and of Chevenard.[110] This compound is probably non-existent (page 51); further, assumption of its existence is unnecessary, consequently there is no need to review this explanation. The Japanese school has denied Fe_2Ni since 1917, at which time Honda and Takagi[131] reported their belief that the low expansion of invar at ordinary temperature is caused by "bringing the temperature of the minimum elongation, or that of the Ar_3 transformation, to the vicinity of room temperature, through a suitable addition of nickel to iron." They believed that gamma-alpha transformation would take place if the alloy were cooled to a temperature sufficiently low. This stand was reversed in 1927 by Honda and Miura,[256] who concluded that invar does not transform in the vicinity of room temperature. They concluded that the low expansion of invar is a "property characteristic of the ferromagnetic alloy in the gamma phase."

Assumption that invar is a two-phase alloy was made by Benedicks and Sederholm,[208] who assumed also that the alloy undergoes transformation with variation of temperature. Since the specific volume of the gamma phase at 36 per cent nickel is less than that of alpha phase, normal thermal expansion upon heating would be compensated by the volume change accompany-

FIG. 125.—Thermal expansion of alloys containing the minimum effective nickel content.

ing transformation. By refined microscopic technique, these workers believed that they proved the existence of two phases; by delicate expansion measurement, they found the required expansion hysteresis. These findings were evidently not uniformly convincing, because Phragmén[394] was led to perform an X-ray investigation of the low-expansion alloys. It was his conclusion that the low expansion is a property of the face-

centered cubic (gamma) phase since no trace of alpha phase could be detected. Chevenard, in discussion of Phragmén's contribution, reiterated other telling evidence against the two-phase hypothesis. Some of it is given in the next section.

79. Chevenard's Explanation.—Chevenard[161] postulated two forms of a ferromagnetic material which differ in density and which undergo reversible transformation, one to the other, upon change of temperature. One form is supposed to be relatively

FIG. 126.—Coefficients of expansion ($\times 10^6$) of iron-nickel-cobalt alloys at ordinary temperature. (*Masumoto.*[391])

stable at low temperature, the other at high temperature. In Fig. 128 (which is directly comparable to Fig. 111, page 152, containing Chevenard's original curves), curve I represents the thermal expansion of the form which is stable at high temperature; this curve is characteristic of non-ferromagnetic substances. Curve II is the observed expansion curve of a 40 per cent nickel alloy. Curve III represents the difference between curves I and II. Evidently the postulated form which is stable at low tem-

FIG. 127.—Thermal expansion of iron-nickel-cobalt alloys.

perature contracts with increased temperature. The maximum contraction is comparable with Chevenard's "total anomaly" (A_0 in Fig. 111). The total anomaly is a function of nickel content; Chevenard's values are given by curve I, Fig. 112.

Fig. 128.—Components of thermal expansion.

Chevenard's explanation of the anomaly-temperature curve is as follows: For convenience the form which exists alone at absolute zero may be denoted A and that which exists at high temperature (above the Curie point) may be denoted B. Then at all temperatures between absolute zero and the Curie point the state of the ferromagnetic substance can be characterized by the fraction of the form A. It is assumed that the specific

volume v of the substance is the rule-of-mixtures value obtained from the specific volumes v_A and v_B of the forms A and B. Thus:

$$v = xv_A + (1 - x)v_B$$

or

$$x = \frac{}{v_A - v_B}$$

The quantity $v - v_B$ is related to the difference curves of Figs. 111 and 128. At absolute zero, $v - v_B = v_A - v_B$ represents the total anomaly. By direct and indirect estimation, Chevenard was able to evaluate the thermal expansion of forms A and B, and thus to compute the variation of the fraction x of the form A with temperature. This curve corresponds almost exactly with the curve of Hegg[84] (page 189) showing the variation with temperature of the square of relative intensity of magnetization $(I/I_0)^2$ of a corresponding alloy (40 per cent nickel).

It follows that the abnormal expansion of all ferromagnetic substances is to be ascribed solely to the fact that they are ferromagnetic. The anomaly (or perhaps ferromagnetic component of expansion) is negative when v_A is uniformly larger than v_B, as is true of alloys of the invar type and of iron carbide, and positive when v_B is uniformly larger than v_A, as is true of nickel and magnetite.

In connection with the foregoing, it may be stated that the final solution of the problem is likely to come from attack in the general direction taken by Dehlinger,[558] who attempted in a preliminary way to evaluate the volume change accompanying spontaneous magnetization.

It is of interest to note that Guillaume[26] in 1897, after discussing magnetization-temperature curves of reversible alloys, stated: "The anomaly of dilatation is probably due to the superposition of two phenomena. One of them produces normal dilatation; the other however causes increase of volume upon cooling."

80. Masumoto's Explanation of Invar.—Masumoto[391] also sought the origin of the low expansion of alloys of iron and nickel in their ferromagnetism. "A typical form of the expansion-temperature curve is shown schematically in Fig. 129 (RQP); thus, with the rise of temperature, the expansion increases almost linearly up to the critical point, at which the rate of change of expansion abruptly increases and assumes another value. In

other words, the gamma solid solution has a smaller expansibility in the ferromagnetic than in the paramagnetic state." Masumoto extrapolated line PQ to room temperature O, then assumed OR to represent "ferromagnetic expansion." Data on this quantity and on intensity of magnetization are assembled

FIG. 129.—Schematic expansion curve.   (*Masumoto.*[391])

in Table 30 since "it is . . . to be expected that the ferromagnetic expansion will be proportional to the saturation magnetiza-

TABLE 30.—EXPANSION AND INTENSITY OF MAGNETIZATION OF IRON-NICKEL ALLOYS*

Property	Nickel, per cent									
	30	32	34	36	40	50	60	70	80	100
Intensity of magnetization, I_0	345	600	890	1090	1250	1246	1181	1030	851	488
Ferromagnetic expansion, $e_f \times 10^3$	0.6	1.45	2.55	3.15	3.55	3.40	2.90	2.43	2	1.30
Ratio, $\dfrac{I_0}{e_f} \times 10^{-2}$	575	414	349	346	352	366	407	424	409	375

* Masumoto.[391]

tion at room temperature. . . . "   Masumoto interpreted the values of the ratio of intensity of magnetization (I_0) to ferromagnetic expansion (e_f) given in Table 30 to mean constancy of the ratio, *i.e.*, as confirmation of his expectation; therefore,

$$e_f = kI_0$$

In Fig. 129, the mean coefficient of expansion α of ferromagnetic alloys is given by the ratio QS/RS. In reversible alloys containing less than 40 per cent nickel, the ferromagnetic-expansion curve "deviates considerably from a straight line"; in this event, Masumoto constructed the tangent to the expansion curve at room temperature; its intersection with the extrapolated non-ferromagnetic-expansion curve "may be called the 'virtual critical point,'" and the mean coefficient of expansion is given by a ratio similar to that already given. It is an experimental fact that the inclination of line OQ is nearly constant for reversible alloys, hence, as an approximation,

$$\alpha = \frac{QS}{RS} = \frac{QA_2 - SA_2}{\theta} = \tan \partial - \frac{kI_0}{\theta}$$

where θ is the "critical point." This indicates that the value of α depends only on the ratio I_0/θ.

On the whole, however, Masumoto's explanation is not very impressive.

D. AUTHOR'S SUMMARY

1. By selecting a proper composition and a proper treatment it is possible to produce iron-nickel alloys having a coefficient of thermal expansion ranging from substantially zero to that of ordinary irons and steels. This fact has led to a variety of applications, among which may be mentioned length standards such as meter bars for metrology and wires and tapes for geodesy; in horology; and lead-in seals for electric lamps. This list by no means exhausts the uses of these alloys, it merely serves to indicate the nature of the application.

2. Alloys especially useful because of their expansion characteristics contain at least 34 per cent nickel; *i.e.*, they are reversible. The one called invar, containing about 36 per cent nickel, is perhaps the best known. At ordinary temperature invar possesses the smallest coefficient of expansion of the series; for example, such an alloy without special treatment after forging has a coefficient of 1 to 2×10^{-6}, as compared with 11 to 12×10^{-6} for iron.

3. It is very important to note that the low coefficient of expansion of invar exists only over a limited temperature range. The range of low expansion varies with impurity content and with

treatment, so no definite values can be given. A safe approxima-
tion, however, is -25 to 100°C. (-15 to 210°F.). Increased
nickel content tends to shift the range of minimum expansion to
higher temperature. Increased nickel content increases also
the value of the minimum coefficient of expansion. This is
illustrated by the curves of Fig. 103, page 146.

4. Factors influencing the coefficient of expansion of low-
expansion alloys are impurity content, mechanical treatment,
and thermal treatment. The ordinary impurities present in
commercial alloys, such as carbon and manganese, increase
the minimum coefficient of expansion and decrease its tempera-
ture range. Mechanical treatment, especially cold work, tends
to decrease the value of the minimum coefficient—even nega-
tive values are possible. Quenching also tends to decrease the
value of the minimum coefficient, but not so markedly as cold
work. Annealing, on the other hand, tends to increase it.

5. Newly made invar is subject to dimensional instability.
Further, there may be transitory length change after a tempera-
ture-change cycle. Factors that affect the length of a specimen
at a given temperature are the temperature to which the specimen
has been heated previously and the rate of approach to the final
temperature. The magnitude of transitory change may be
indicated by the following data obtained by Guillaume (page
157): At 15°C. (60°F.), immediately after forging, a bar of invar
elongated at the rate of 0.07 to 0.08 micron per m. per day, but
only 0.03 micron per m. per day after annealing at 40°C. (105°F.).
After long storage at room temperature, contraction at 100°C.
(210°F.) was complete in about 30 min., but required several
days at 40°C. (105°F.).

In addition to transitory change of length, there are long-
duration changes. To reduce their magnitude, Guillaume
invented a process of aging, which consists of forging, then
cooling to room temperature from, for example, 100°C. (210°F.)
over a period of 2 or 3 months.

According to Guillaume (page 160), the cause of dimensional
instability of invar-type alloys is the presence of carbon. This
conclusion is supported by the curves of Fig. 117, page 159.
Instability of materials treated to produce the smallest coefficient,
as by cold work after quenching, may be expected even though
the carbon content is low, however. The small coefficients

obtained by such methods tend to revert to normal values with lapse of time.

Length changes of the kind described are of little significance for ordinary purposes; they are of importance in such applications as geodetic tapes and wires. If stabilized by special treatment, such equipment must be used within the atmospheric range of temperature, otherwise stability is lost.

6. Data assembled in Fig. 118, page 160, show that the coefficient of expansion of (alpha) iron at ordinary temperature is decreased somewhat by the addition of nickel; this is true also of the coefficient of expansion of nickel upon addition of iron. The coefficient of gamma-phase alloys is minimum at about 36 per cent nickel.

7. The addition of such elements as carbon, manganese, copper, chromium, molybdenum, and tungsten increases the value of the minimum coefficient of low-expansion iron-nickel alloys. Manganese, chromium, molybdenum, and tungsten increase the nickel content for minimum coefficient, and copper and carbon decrease it. Silicon up to at least 1 per cent has no appreciable effect on the minimum coefficient.

8. Alloys having zero coefficient of expansion can be obtained, without cold working, by substitution of cobalt for some of the nickel of invar-type alloys.

9. The most plausible explanation of low-expansion alloys seems to be closely allied with that of Chevenard (page 176). Abnormal expansion is clearly associated with ferromagnetism. Quantitative details cannot yet be worked out, but it seems likely that future understanding of such matters as volume change accompanying spontaneous magnetization will provide these quantitative details.

CHAPTER VII

MAGNETIC PROPERTIES OF IRON-NICKEL ALLOYS

Historical—Magnetization of Iron-nickel Alloys—Permeability of Iron-nickel Alloys—Coercive Force and Residual Induction—Cyclic Energy Losses—Directional Ferromagnetic Properties—Author's Summary

Iron and nickel are the two most common ferromagnetic elements and their gamma-phase alloys have become important magnetic materials within recent years, especially in the communication industries. Modern standards of transmission efficiency require that the materials used in the various circuits produce the maximum magnetic effect with minimum energy loss and current distortion, which means that high permeability and low hysteresis loss are required at low inductions, *i.e.*, less than 1000 gausses. A requirement for some apparatus is that permeability shall remain constant, or nearly so, over the operating range of inductions; this is met in several ways. Eddy-current losses are reduced to a minimum by using alloys having the highest possible electric resistivity obtainable with the desired magnetic properties, and by using cores composed of thin laminations or of compressed, insulated powder; consequently the materials must be suitable for the fabrication operations. For such apparatus as current transformers and signaling and switching relays, the properties at medium and high inductions are important as well; here high permeability, low coercive force, and high electric resistivity make possible the greatest sensitivity and speed of operation. One of the earliest applications of high-nickel alloys was in the construction of submarine telegraph cables to increase the inductance of the cable, which permitted a substantial increase of signaling speed. Other well-known applications have been in apparatus such as audio-frequency transformers and chokes for radio amplifiers, telephone repeaters, and magnetic shields.

Many of the essentially binary alloys of iron and nickel used in the foregoing apparatus are being supplanted by others con-

184

taining relatively small proportions of such elements as chromium or molybdenum; these alloys, and others containing additional elements, are discussed in the next chapter. Magnetic alloys containing chiefly iron and nickel are well known as "permalloys"; another well-known alloy, containing about 50 per cent nickel, is known as "hipernik." Other names are listed at the end of this chapter. It is difficult to estimate the production of these alloys, although available statistical data for the United States indicate that they have been produced at rates as great as several million pounds per year.

It may be useful to review the principal magnetic terms. Figure 130 shows the upper half of a schematic hysteresis loop

Fig. 130.—A schematic hysteresis loop and the corresponding initial magnetization curve.

and the initial magnetization curve (broken) that is obtained from a fresh or previously demagnetized material. The unit of field strength, or magnetizing force, H, is the oersted. That of magnetic induction B is the gauss. The intensity of magnetization I is defined by $I = \dfrac{B - H}{4\pi}$. Intrinsic induction, or ferric induction, is given by $4\pi I = B - H$. Permeability (μ) is defined as the ratio of induction to field strength, or $\mu = B/H$. Residual induction (B_r), as is shown by the schematic loop, is that which remains when the field strength is reduced to zero. The coercive force (H_c) is the reverse field strength required to reduce the induction to zero. The hysteresis loss (W_h) in ergs per cubic centimeter is the area of the hysteresis loop in gauss-oersteds divided by 4π. Other terms are defined as they appear.

A. HISTORICAL

Evidently Hopkinson;[9] in 1889, was the first to determine magnetic properties of an iron-nickel alloy—containing 25 per cent nickel and supplied by Riley (page 368). This report was followed a year later by another[12] which contained data on magnetic properties of more alloys from the same source. One contained 77 per cent nickel, and Hopkinson's discussion of it is of interest:

In Curve 17 [not reproduced] is given the relation of induction and force at ordinary temperature. It is curious to remark that the induction for considerable forces is greater than in the steel with 33 per cent nickel, and it is greater than for a mechanical mixture of iron and nickel in the proportions of the analysis, however the particles might be arranged in relation to each other.

This was clearly immediate recognition that the magnetic properties of iron-nickel alloys do not follow the rule of mixtures.

Of historical interest also are data obtained by Barrett, Brown, and Hadfield,[39] who determined induction curves for field strengths up to 45 oersteds for a series of alloys containing up to 31.4 per cent nickel, up to 1 per cent carbon, and variable silicon and manganese. Some of these are reproduced in Table 31. Similar results were obtained by Carpenter, Hadfield, and Longmuir[59] on alloys containing up to 20 per cent nickel.

TABLE 31.—MAGNETIC PROPERTIES OF SOME IMPURE IRON-NICKEL ALLOYS*

Nickel, per cent	Induction for H = 45 oersteds, gausses	Permeability for H = 8 oersteds	Residual induction, gausses	Coercive force, oersteds	Hysteresis loss, ergs per cu. cm. per cycle, at 45 oersteds
1.92	16,000	1380	9140	2.67	15,300
3.82	16,190	1375	9320	2.76	15,860
4.75	10,500	125	6910	14.28	39,800
11.39	8,190	118	4630	17.33	32,050
12.10	4,170	....	....	22.40	21,850
12.70	4,480	....	....	22.10	24,280
19.64	7,770	90	4770	20.00	36,850
24.50	4,230	32	2790	22.50	22,200
31.40	4,460	357	1720	0.50	803

* Barrett, Brown, and Hadfield.[39]

81. The First Extensive Investigations.—The first extensive investigation was reported by Burgess and Aston[81] in 1910. Alloys containing up to 75 per cent nickel were tested in several conditions of thermal treatment. For the as-forged condition, induction curves for alloys containing 0.27 and 1.92 per cent nickel lay slightly below the curve for a bar of unannealed electrolytic iron. Further increase of nickel content, to about 20 per cent, caused greater decrease of magnetizability, although increase to 35, 47, and 75 per cent nickel "restored the magnetic quality very markedly." The ferromagnetism of gamma-phase iron-nickel alloys was noted in the same year by Panebianco,[85] who tested alloys containing 36 and 49 per cent nickel in fields down to 0.016 oersted, and found initial permeabilities of about 700 and 550 respectively. These values were greater than that obtainable for iron at that time. Magnetic properties in weak fields, or, more significantly, at inductions of 1000 gausses or less, are very important in telephony, and it was in the interest of this art that the first comprehensive investigation of the magnetic properties of iron-nickel alloys was begun by Elmen[297] in 1913. Results of this work are reviewed in detail elsewhere, as are those of Yensen,[157] who was next after Burgess and Aston to publish details of a long investigation of properties at high inductions.

B. MAGNETIZATION OF IRON-NICKEL ALLOYS

It is frequently of interest to know the extent to which a material is magnetizable. This information is ordinarily given in terms of saturation magnetization, $4\pi I_\infty = (B - H)_\infty$. It is also of interest to know the extent of magnetization for lower field strengths. This portion of the chapter is concerned with such matters, including the variation of magnetization with composition, temperature, and pressure.

82. Saturation Magnetization of Iron-nickel Alloys.—So far as alpha-phase alloys are concerned, it can be stated that there is little change of saturation magnetization with nickel content. The best value for iron at ordinary temperature is

$$4\pi I_\infty = 21{,}580 \pm 10 \text{ gausses,}$$

arrived at by Steinhaus, Kussmann, and Schoen[614] by extrapolation to zero content of impurity.

Saturation magnetization of gamma-phase alloys at ordinary temperature is given in Fig. 131. Excepting Lichtenberger's[421] results on single crystals, reported values are in fair agreement, especially those of Hegg,[84] Peschard,[221] McKeehan and Cioffi,[239] Schulze,[286] and Dahl and Pawlek.[523] Points of Yensen,[157] Gumlich,[214] and Masumoto[308] are somewhat

FIG. 131.—Saturation magnetization of iron-nickel alloys.

scattered but are seldom far from the curve. It appears that saturation magnetization increases from about 6500 gausses for nickel to a maximum of about 16,000 gausses at about 47 to 48 per cent nickel, then declines rapidly as 30 per cent nickel is approached.

In Fig. 132 is given saturation magnetization at absolute zero, as estimated from extrapolated values of Hegg[84] and of Peschard.[221] Throughout the range of composition the curves

show greater saturation magnetization than would be expected from a linear relation between iron and nickel, and the greatest deviation appears to exist in the vicinity of 30 per cent nickel. There is some indication of a maximum at about 10 per cent nickel in Peschard's original curves.

83. Influence of Temperature on the Magnetization of Iron-nickel Alloys.—An extensive investigation of the variation with

Fig. 132.—Approximate saturation magnetization of iron-nickel alloys at absolute zero.

temperature of the magnetization of iron-nickel alloys was reported as early as 1910 by Hegg.[34] Only nominal compositions (steps of 10 per cent) were given, consequently uncertainty is to be expected—especially in ranges in which magnetization changes sharply with composition. Results were reported in terms of magnetic moment per gram. Some of these data were converted to terms of saturation magnetization by means of the X-ray specific volumes quoted in Chapter V; they are given in Fig. 133 for alloys containing 40, 60, and 80 per cent nickel. These curves are consistent with Figs. 131 and 132 except for

the 40 per cent nickel alloy at room temperature, for which a value of about 15,800 gausses is indicated.   This is a few hundred gausses more than is shown by Fig. 131.   There is, however, uncertainty about the specific volume in this region in addition to that of composition.   Furthermore, the maximum of the curve of Fig. 131 may be low by several hundred gausses for high-purity alloys.

Alloys having a large negative temperature coefficient of magnetization in the vicinity of room temperature are of interest

ᴜ. 133.—The influence of temperature on the magnetization of some iron-nickel alloys.

for such applications as compensating devices.   Those containing about 30 per cent nickel are suitable, because, according to Stäblein,[613] the change of induction in a field of 100 oersteds is about 50 gausses per °C. in the vicinity of 20°C.

84. Magnetic Induction of Iron-nickel Alloys.—The induction for various field strengths of iron-nickel alloys is given in Fig. 134. These curves were constructed from data of Yensen[157] and of Masumoto.[308]   (Masumoto's data were reported originally as intensity of magnetization.)   Agreement is good for field strengths of at least 20 oersteds.   The curves for alpha-phase alloys show decreased induction for a given field strength as

nickel content is increased (there may be a small maximum for high field strengths near 5 per cent nickel), whereas gamma-phase alloys show a maximum of induction in the neighborhood of 50 per cent nickel in fields of medium and high strength.

Fig. 134.—Magnetic induction of iron-nickel alloys for various field strengths.

85. Effect of Hydrostatic Pressure on Induction.—The effect of pressure on the induction of a series of annealed iron-nickel alloys, nominally containing nickel in steps of 10 per cent, was measured by Steinberger.[469] The principal effects found (excepting the 30 per cent nickel alloy, which became nearly non-ferromagnetic upon application of the highest pressure, in the neighborhood of 12,000 kg. per sq. cm. or 170,000 lb. per sq. in.) were: (1) The first application of pressure caused a rela-

tively large change of induction, usually a decrease; the recovery was incomplete upon removal of the pressure.   (2) The sign of the pressure effect depended upon the field strength.   The field strength at which the sign reversed depended on the temperature, the degree of cold work of the specimen, and the annealing treatment.   Steinberger's results were given in numerous curves which should be consulted in the original for details.

C. PERMEABILITY OF IRON-NICKEL ALLOYS

The permeability of a material is defined as the ratio of induction to field strength.   There is no name for unit permeability, and before differentiation was made between the gauss and the oersted a few years ago, this quantity was always reported as a dimensionless number.   Since the unit of field strength is now the oersted, and the unit of induction is the gauss, unit permeability is expressed by gausses per oersted.   No confusion can result, however, from omission of "gausses per oersted."

The permeability of iron-nickel alloys, especially at low induction, is highly structure sensitive.   For applications requiring the highest permeability of which the material is capable, careful annealing is usually, but not always, essential, as is the avoidance of permanent mechanical strain in subsequent operations.   High permeability is sometimes sacrificed, however, in order to obtain certain other effects, such as constancy of permeability over a range of field strengths.

86. Discovery of High-permeability Alloys of Iron and Nickel. Certain alloys of iron and nickel found application in the communication industry during 1917.   The first paper to describe them, by Arnold and Elmen,[184] appeared in 1923.   In the light of subsequent developments, it seems worth quoting from their introduction:

Some years ago it was discovered in this laboratory that certain nickel-iron alloys, when properly heat treated, possess remarkable magnetic properties.   These properties are developed in alloys which contain more than 30 per cent of nickel. . . . The entire range . . . exhibits these properties to some degree and offers new possibilities. . . . The most startling results, however, are obtained with alloys of approximately 80 per cent nickel . . . whose permeabilities at small field strengths are many times greater than any hitherto known.   For convenience we call these peculiarly magnetic alloys by the general name

"permalloy." . . . The development of permalloy has assured us a revolutionary change in submarine-cable construction and operation, and promises equally important advances in other fields of usefulness.

Arnold and Elmen used specimens in the form of tape and exercised care to maintain constancy of size, shape, and mechan-

FIG. 135.—The permeability of some iron-nickel alloys as a function of induction.

ical conditions. The aforementioned proper heat treatment required cooling through a proper temperature range at a proper rate. The temperature range seemed to extend from just above the magnetic inversion to about 300°C. (570°C.). The treatment finally adopted consisted of heating to 900°C. (1650°F.) and cooling slowly. The material was then reheated to 600°C. (1110°F.) and finally cooled quickly by placing it on a copper

plate at room temperature. (This "permalloy treatment" appears often in the literature.) With the heat treatment established, the best composition was sought; it was found to be about 78.5 per cent nickel.

The largest value of initial permeability (μ_0) found at ordinary temperature was about 13,000. A good average value is 10,000,

FIG. 136.—Hysteresis loops of ingot iron and of a 78.5 per cent nickel alloy.
(Arnold and Elmen.[184]*)*

and this is the value indicated by curve 2 of Fig. 135, which was constructed from data of Arnold and Elmen. The maximum permeability shown is about 87,000, "not exceptionally high" for the material. The difference between the 78.5 per cent nickel alloy and ingot iron is shown well by the hysteresis loops of Fig. 136.

Other data included in Fig. 135 were given by Elmen[527] for other specimens of the 78.5 per cent and a 45 per cent nickel

alloy iron-nickel. These are by no means limiting values; for example, Cioffi[408] found an initial permeability of 20,000 and a maximum permeability of 340,000 for a specimen of hydrogen-treated ingot iron. Yensen,[403] by special treatment, which included long annealing at high temperature in hydrogen, of a 50 per cent nickel alloy, has found maximum permeabilities as high as 167,000. Elmen[527] reported 11,000 initial and 227,000 maximum for a 45 per cent nickel alloy and also[297] 13,000 initial and 405,000 maximum for a 78.5 per cent nickel alloy. But this

FIG. 137.—The reversible permeability of an annealed 45 per cent nickel iron-nickel alloy for an alternating field of 0.0032 oersted at 200 cycles. (*Elmen*.[527])

was not the end: in 1935, Dillinger and Bozorth[526] found a maximum permeability of 610,000 for a specially treated 65 per cent nickel alloy (page 213), and recently the 1,000,000 mark was passed in a 66 per cent nickel alloy and in other materials.[587] It is to be inferred that the highest possible permeability is unknown.

87. Reversible Permeability of Iron-nickel Alloys.—Reversible permeability (μ_r), *i.e.*, the initial alternating-current permeability during direct-current magnetization, which is to say μ for $\Delta H \rightarrow 0$, is important in apparatus in which both alternating and direct current are involved. Measurement of reversibility over a range of direct-current fields results in "butterfly curves" of the kind shown in Figs. 137 and 138 for alloys containing 45 and 78.5 per cent nickel, given by Elmen.[527] The criterion of

FIG. 138.—The reversible permeability of an annealed 78.5 per cent nickel iron-nickel alloy for an alternating field of 0.000984 oersted at 200 cycles. (*Elmen.*[527])

FIG. 139.—The effect of heat treatment on the initial permeability of iron-nickel alloys.

fitness of a material for such apparatus is often the flatness of the curve over the operating range of the direct-current field, or, more generally, the magnitude of the reversible permeability at the operating field strength.
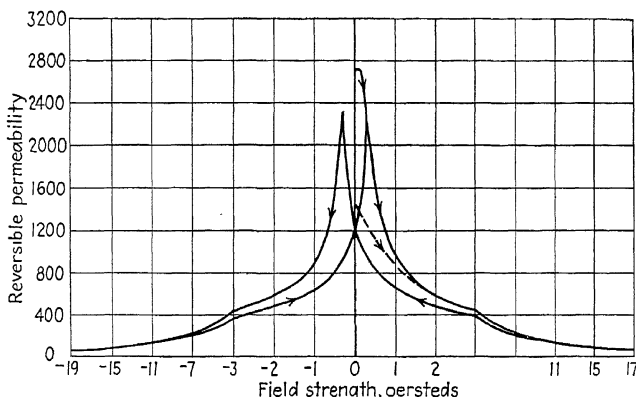
88. Influence of Heat Treatment on Permeability.—The necessity of special heat treatment to obtain the highest initial permeability in high-nickel iron-nickel alloys has been mentioned. Detailed information was given by Elmen[297] and by Gumlich, Steinhaus, Kussmann, and Scharnow.[276] This is summarized for comparison in Fig. 139. The highest initial permeability shown by Elmen's data for alloys in the vicinity of 78 per cent nickel was obtained by annealing at 900 to 1000°C. (1650 to 1830°F.) for 1 hr., reheating to 600°C. (1110°F.) and holding 15 min., then cooling rapidly on a copper plate in air. Another treatment consisted of the first annealing operation only, *i.e.*, without the reheating and rapid cooling operations. Still other annealed specimens were reheated to 425°C. (795°F.) for 24 hr. or longer; this treatment was termed "baking." It was continued until there was no further decrease of permeability. The least time was required by alloys containing 60 to 80 per cent nickel; as nickel content approached 40 per cent or 90 per cent, the time increased to as much as several weeks, and beyond these limits there was seemingly no change.

A larger number of treatments was investigated by Gumlich and his coworkers after preliminary trial of one consisting of heating to 930°C. (1705°F.) for 5 to 10 min., then cooling rapidly; the three shown in Fig. 139 consisted of

I. Vacuum annealing at 1050°C. (1920°F.) for 5 hr. followed by slow cooling.

II. Reheating the same specimens to 600°C. (1110°F.), then cooling quickly.

III. Reannealing the specimens at 1050°C. (1920°F.) for 5 hr. and cooling rapidly from 600°C. (1110°F.).

Such series of heat treatments are likely to lead to confusing results because of such factors as recrystallization and reaction with the furnace atmosphere. Further, comparison of the results of various investigators is likely to be difficult because of divergent cooling rates. The trends indicated by the data of Fig. 139, and also those of Schulze,[286] are in general agreement, however.

Heat treatment also has a large effect on maximum permeability. For example, Elmen[297] found a value of 10,000 for an annealed 78.5 per cent nickel alloy, as compared with 87,000 for the same alloy after reheating to 600°C. (1110°F.) and cooling rapidly. The rate of cooling is important also. Tests on a sample of a 78.5 per cent nickel alloy yielded the curves of Fig. 140. The highest initial permeability resulted from a cooling rate [from 600°C. (1110°F.)] of about 20°C. (35°F.) per sec., whereas a rate about 4 times as great resulted in the highest

Fig. 140.—The effect of cooling rate on initial and maximum permeabilities of a 78.5 per cent nickel alloy. (Elmen.[297])

maximum permeability. Heat treatment in a magnetic field is discussed later.

89. Influence of Temperature on Permeability of Iron-nickel Alloys.—The variation of initial permeability with temperature of a 78.5 per cent nickel alloy was measured by Elmen.[297] Originally heat treated to produce the highest initial permeability, the specimen was carried through the temperature cycle ranging from ordinary temperature to 650°C. (1200°F.) in a constant field of 0.003 oersted. Results, given in Fig. 141, show that permeability at the start was 7000; it increased rapidly to about 12,700 at 315°C. (600°F.), then decreased to about 3600 at 500°C. (930°F.), after which it increased to a sharp maximum at about 530°C. (985°F.); upon further increase of temperature, the alloy

became non-ferromagnetic at about 550°C. (1020°F.). Upon cooling, the permeability did not retrace the values obtained upon heating, and from about 450°C. (840°F.) downward it remained nearly constant at about 2000. Reheating the specimen to 600°C. (1110°F.) followed by rapid cooling, however, restored the permeability to its original value.

In general, important details of the permeability-temperature curves of such materials are the temperature coefficients for the

FIG. 141.—The effect of temperature on the initial permeability of a 78.5 per cent nickel alloy. (*Elmen.*[297])

initial and final states, and the temperature at which, if exceeded, the curve becomes irreversible.

The variation of initial permeability with temperature of a 31 per cent nickel alloy was given by Goldschmidt.[414] In this instance also a maximum was observed [at about −35°C. (−30°F.)], but it was much less sharp; in addition, the decline of permeability with further increased temperature was gradual rather than steep.

90. Effect of Strain on Permeability.—Mechanical strain can have considerable effect on the permeability of a ferromagnetic material. In gamma-phase alloys, Buckley and McKeehan[209] found the effect to depend upon nickel content. For example, the permeability of a 65 per cent nickel alloy in weak and medium fields was increased markedly by the application of a tensile stress of 5000 lb. per sq. in. The same stress markedly decreased the permeability of an 85 per cent nickel alloy. Buckley and McKeehan placed the composition of inversion at about 81 per cent nickel. The foregoing effect is related closely to the magnetostrictive effects which are discussed in detail in Chapter IX. Other results were reported by von Auwers[330] on alloys containing 36, 40, 46, 60, and 78.5 per cent nickel. Permeability for these alloys was maximum at field strengths between 0.1 and 0.5 oersted. The maximum permeability of the 36 per cent nickel alloy in the unstressed state was about 7000; this was increased to 13,000 by a stress of 7500 lb. per sq. in. and to 17,000 by 18,700 lb. per sq. in. Increases for the 40 and 46 per cent nickel alloys were similar in magnitude, but the application of 9800 lb. per sq. in. increased the maximum permeability of the 60 per cent nickel alloy only from 18,000 to about 20,000. The increase for the 78.5 per cent nickel alloy was again marked, being from 40,000 to about 65,000 for a stress of 14,200 lb. per sq. in. Buckley and McKeehan,[209] on the other hand, also tested a 78.5 per cent nickel alloy; maximum permeability was increased from 60,000 to 280,000 by applying a stress of 3560 lb. per sq. in. A few other data on alloys of this composition were given by Preisach.[427]

The effect of hydrostatic pressure up to 1000 kg. per sq. cm. (14,200 lb. per sq. in.) was investigated by von Auwers; it was found to be more complicated, because the maximum permeability of the 36 per cent nickel alloy was increased (in the neighborhood of 1000 units), whereas the maximum permeability of the 40, 46, and 60 per cent nickel alloys underwent decrease upon the application of pressure. The effect on the 78.5 per cent nickel alloy was slight, the only clearly discernible difference being the displacement with increased pressure of the maximum permeability to lower field strengths.

Strain, such as is produced by cold working and phase transformation, is often more complicated than that produced by

simple tensile loading of a wire. It is well known that there is a certain parallelism between the magnetic "hardness" so produced and mechanical hardness. The connection between permeability and internal strain produced by cold rolling a 65 per cent nickel alloy is illustrated by the curves in Fig. 142, obtained by Haworth.[598] The curve for internal strain shows values based on the angular width of a diffracted X-ray beam. It is to be seen that both initial and maximum permeabilities increased rapidly for annealing temperatures between 400 and 600°C. (750 and 1110°F.); this range is the lowest in which recrystal-

FIG. 142.—The effect of internal strain on permeability. (*Haworth.*[598])

lization, consequently relief of strain, will proceed. Inhomogeneous internal strain is clearly inimical to high permeability.

A relation between initial permeability and internal stress was proposed by Kersten;[386] this is

$$\mu_0 = \frac{0.018(B - H)_\infty^2}{(\Delta l/l)_c \sigma_i}$$

where μ_0 is initial permeability, $(B - H)_\infty$ is saturation magnetization, $(\Delta l/l)_\infty$ is saturation magnetostriction, and σ_i is internal stress, without reference to sign, in dynes per square centimeter. In the absence of internal strain caused by cold working and the presence of impurity, there is ordinarily still present strain caused by magnetostriction; in this instance, the stress is the

product of the modulus of elasticity E and saturation magneto-strictive strain; *viz.*

$$\sigma_i = E\left(\frac{\Delta l}{l}\right)_o$$

The equation for the theoretical upper limit of initial permeability becomes

$$\mu_0 = \frac{0.018(B - H)_\alpha}{(\Delta l/l)_\infty{}^2 E}$$

Such limits are compared with observed values in Fig. 143, which was given by Bozorth.[514] Another comparison, based on different data, was made by Kersten.[386]

Fig. 143.—Comparison of the theoretical upper limit of initial permeability with the highest initial permeabilities observed for iron-nickel alloys. (*Bozorth.*[514])

Several facts emerge from the foregoing information on the effect of strain. (1) Permeability, *i.e.*, ease of magnetization, may be either increased or decreased by the application of a homogeneous uniaxial stress, as by simple tensile loading of a wire; the direction of the effect is the same as that of the magneto-strictive effect. (2) The permeability is ordinarily lowered by the presence of inhomogeneous strains. (3) Qualitative estimates of the connection between strain and permeability have been

fairly successful, but a rigidly quantitative treatment remains to be made.

91. Combined Effect of Mechanical and Thermal Treatments. Investigators of iron-nickel alloys for special purposes soon found that the magnetic properties—especially permeability— could be changed markedly by various combinations of mechanical and thermal treatments. Yensen,[227,438] for example, investigated their effect on the maximum permeability of 50

Fig. 144.—Influence of hot rolling and subsequent annealing on the maximum permeability of a 50 per cent nickel iron-nickel alloy melted in vacuum. (*Yensen.*[438])

per cent nickel alloys, initially 1 in. thick. This material was hot rolled with increasing degrees of reduction, then annealed 8 hr. at 1000°C. (1830°F.) in vacuum. No considerable change took place for reductions up to 94 per cent, but further reduction to 98.6 per cent caused a rapid drop of maximum permeability from 20,000 to 2000. To learn whether oxidation during hot rolling was responsible for the loss of permeability, Yensen then tried cold rolling, but no improvement resulted. Another possibility was the presence of oxygen or oxides in the original material; this led to annealing in hydrogen for 8 hr. at 1000°C. (1830°F.). Results are shown in Fig. 144. It was in agreement with the

hypothesis of oxygen removal by hydrogen that the treatment was most effective for the thinnest specimens, in which diffusion would be most complete.

Hagemann and Hiemenz[449] tested tapes, 0.1 and 0.02 mm. (0.004 and 0.0008 in.) thick, prepared from an alloy containing 47 per cent nickel and 1 per cent manganese. The tapes were annealed in vacuum, hydrogen, nitrogen, and in air at 900°C. (1650°F.). As separating materials during annealing, magnesia, sand, lime, carborundum, alumina, and paper were used. Initial and maximum permeabilities are given in Tables 32 and 33. Most values for the 0.1-mm. (0.004-in.) material were greater than corresponding values for the thinner material; however, the highest maximum permeability observed (27,800) was for the thinner material annealed in hydrogen with paper as the separating material.

Directional effects in rolled iron-nickel alloys have been investigated at length by Dahl and his coworkers.[445,523,537,557]

TABLE 32.—INITIAL PERMEABILITY OF VARIOUSLY TREATED STRIPS OF ALLOY CONTAINING 47 PER CENT NICKEL AND 1 PER CENT MANGANESE*

Separating material	Annealed in vacuum		Annealed in hydrogen		Annealed in nitrogen		Annealed in air	
	Thickness, mm. (0.004 and 0.0008 in.)							
	0.1	0.02	0.1	0.02	0.1	0.02	0.1	0.02
Magnesia......	2000	1700	2200	1700	2000	500	2000	1900
Sand..........	2200	1500	2300	1600	1700	500	2000	1700
Lime..........	2100	1500	2100	2400	1600	900	2100	1000
Carborundum..	2200	1100	2100	1600	1600	700	2200	800
Alumina.......	2200	1400	2200	1700	2200	600	2000	1900
Paper..........	2100	1500	2100	2000	2000	2000	1900	1800

* Hagemann and Hiemenz.[449]

Dahl, Pfaffenberger, and Sprung[445] prepared a series of alloys from charcoal iron and shot nickel with additions of 0.5 to 1 per cent manganese. The ingots were rolled to sheet, annealed 2 hr. in hydrogen at 950 to 1000°C. (1740 to 1830°F.), then (1) cooled in air, (2) cooled in the furnace, or (3) quenched in water.

TABLE 33.—MAXIMUM PERMEABILITY OF VARIOUSLY TREATED STRIPS OF ALLOY CONTAINING 47 PER CENT NICKEL AND 1 PER CENT MANGANESE*

Separating material	Annealed in vacuum		Annealed in hydrogen		Annealed in nitrogen		Annealed in air	
	Thickness, mm. (0.004 and 0.0008 in.)							
	0.1	0.02	0.1	0.02	0.1	0.02	0.1	0.02
Magnesia......	19,800	6200	18,200	5,700	7,400	800	22,400	8600
Sand..........	19,900	5600	18,400	5,900	4,800	800	21,500	8600
Lime..........	16,500	6400	14,700	22,200	5,800	2,900	17,800	1600
Carborundum..	12,600	3500	15,800	4,500	4,200	1,600	12,200	1700
Alumina.......	19,300	4700	17,500	6,300	12,300	900	21,400	9400
Paper..........	18,500	5000	16,100	27,800	15,000	17,100	19,500	8500

* Hagemann and Hiemenz.[449]

The first results of interest are on the variation of initial permeability with composition for alloys reduced 90 per cent by cold rolling; these are given in Fig. 145. Initial permeability decreased

FIG. 145.—The initial permeability of variously treated iron-nickel alloys after 90 per cent reduction by cold rolling. Preliminary treatment consisted of annealing under hydrogen for 2 hr. at 950 to 1000°C. (1740 to 1830°F.). (*Dahl, Pfaffenberger, and Sprung.*[445])

with increased nickel content to a minimum at about 70 per cent nickel, passed through a small maximum at about 85 per cent nickel, then approached the lowest value as 100 per cent nickel

was approached.   The effect of cooling rate was small, although
the slowest cooling clearly yielded the lowest initial permeability.

As a measure of the ability of a material to recover its original
initial permeability after subjection to a temporary strong magnet-

FIG. 146.—Instability of variously treated iron-nickel alloys after 90 per
cent reduction by cold rolling. Preliminary treatment consisted of annealing
under hydrogen for 2 hr. at 950 to 1000°C. (1740 to 1830°F.).   (*Dahl, Pfaffen-
berger, and Sprung.*[445])

ization, Dahl, Pfaffenberger, and Sprung defined "instability"
s by

$$s = \frac{\mu_0 - \mu_r}{\mu_0}$$

where μ_r is the reversible permeability measured at the point of
the hysteresis loop representing residual induction.   Their
results for iron-nickel alloys reduced 90 per cent by cold rolling,
given in Fig. 146, show the least instability in the 40 to 65 or
70 per cent nickel range.   The most conclusive indication,
however, is that instability is little affected by heat treatment
before rolling.

The effect of degree of reduction on the initial permeability
of the 40 per cent nickel alloy is shown by Fig. 147.   Initial

permeability was decreased rapidly by the first stages of cold rolling; after passing through a minimum for about 40 per cent reduction, initial permeability then increased appreciably (about 30 per cent). This follows from the finding of Six, Snoek, and Burgers[509] that drastic rolling arranges preferred axes parallel to the rolling direction.

Various rolling and annealing treatments lead to non-random— or fiber—structures or textures. Since magnetic properties are

FIG. 147.—The effect of the degree of reduction by cold rolling on the initial permeability of a 40 per cent nickel iron-nickel alloy. (*Dahl, Pfaffenberger, and Sprung.*[445])

sensitive to crystal orientation, sheet having a fiber structure has different magnetic behavior from that composed of grains of random orientation. The magnitude of this difference of behavior in iron-nickel alloys containing 40 to 90 per cent nickel was investigated by Dahl and Pawlek,[523] using alloys prepared as described on page 224. In the fiber-structure specimens the fiber ([100]) was well developed in the 40, 50, and 90 per cent nickel alloys; other alloys showed in addition a second ordering. Permeability measurements are shown in Figs. 154 and 155, pages 213 and 215. According to Dahl and Pawlek, the fiber structure caused a straightening of the magnetization curves for the

40 and 50 per cent nickel alloys. Magnetizability was reduced slightly in the 90 per cent nickel alloy, and the intermediate alloys showed little difference of behavior from that of alloys of random structure.

Pawlek[537] found the following structures in alloys containing more than 30 per cent nickel after cold rolling and after recrystallizing by annealing: (1) after rolling, a mixture of (110) as the

FIG. 148.—The recovery of initial and maximum permeabilities upon annealing of a 40 per cent nickel iron-nickel alloy reduced 80 per cent by cold rolling. (*Pawlek.*[537])

rolling plane with [1$\bar{1}$2] as the rolling direction and of (112) as the rolling plane with [1$\bar{1}$1] as the rolling direction; (2) after recrystallization, (010) as the rolling plane with [100] as the rolling direction (cubic texture). After 80 per cent reduction, followed by annealing at 490 to 500°C. (915 to 930°F.), a random structure resulted, but with 90 per cent reduction and the same annealing treatment, ordering recurred. The recovery of initial and maximum permeabilities upon annealing at various temperatures

in the 40 per cent nickel alloy after 80 and 98.5 per cent reductions is shown in Figs. 148 and 149.

The foregoing investigation was continued by Dahl and Pawlek[557] with unannealed strips of 40 per cent nickel alloys cut 0, 35, 45, 60, and 90 deg. to the rolling direction. Results, plotted in polar coordinates, show that initially random arrangement of the grains leads to quasi-isotropy of properties, because

FIG. 149.—The recovery of initial and maximum permeabilities upon annealing of a 40 per cent nickel iron-nickel alloy reduced 98.5 per cent by cold rolling (*Pawlek.*[537])

initial and maximum permeabilities appear as nearly concentric circles. Increased reduction by rolling leads to fiber structure, which results in pronounced directional effects, as judged by magnetic properties. This is shown by Fig. 150 for 94 per cent reduction. At 50 per cent reduction, for which results are not reproduced here, anisotropy was clear for all properties excepting maximum permeability.

Consideration of the structures found in cold-worked and annealed sheet led Dahl and Pawlek to the conclusion that some

of the magnetic properties have fourfold symmetry. This is true, for example, of residual induction and of permeability for

FIG. 150.—Directional dependence of the properties of a 40 per cent nickel iron-nickel alloy, cold rolled 50 per cent, annealed at 1000°C. (1830°F.), then reduced 94 per cent by cold rolling. (*Dahl and Pawlek.*[557])

certain ranges of field strength. These and the other symmetry relations are shown in Fig. 151. Tests by means of mechanical properties did not lead to complete agreement with expectations.

FIG. 151.—Directional dependence of the properties of a 40 per cent nickel iron-nickel alloy having fiber structure, produced by cold rolling 50 per cent, annealing at 700°C. (1290°F.), cold rolling 98.5 per cent, then annealing at 1100°C. (2010°F.). (*Dahl and Pawlek.*[557])

X-ray examination proved the existence of a second texture that might have been responsible.

Reduction by rolling of material with the cubic texture did not lead at once to the fiber structure (as opposed to the sheet with the random arrangement). Initial permeability was decreased by about the same amount in the two instances however, but the decrease of maximum permeability was much more rapid in the first instance. The change was such that initial and maximum permeabilities approached each other in value. A material having initial and maximum permeabilities nearly alike is of importance in the construction of certain communication equipment. Such material must be used with the applied

Fig. 152.—Directional dependence of the properties of a 40 per cent nickel iron-nickel alloy, cold rolled 98.5 per cent, annealed at 1000°C. (1830°F.), then cold rolled 50 per cent. (*Dahl and Pawlek.*[557])

field parallel to the rolling direction. That there is great difference between the two permeabilities in a direction perpendicular to the rolling direction is shown well by Fig. 152.

A somewhat similar line of investigation has been pursued by Snoek.[543] According to his results, all iron-nickel alloys containing more than 30 per cent nickel can be made highly anisotropic by reduction of more than 99 per cent by rolling, followed by partial annealing. This treatment causes all grains to be oriented so definitely with respect to the strip that the strip behaves nearly as a single crystal with one axis parallel to the strip, and with one cube face in the surface of the strip. Further reduction of about 30 per cent causes high magnetic anisotropy,

with the direction of easiest magnetization lying only in the plane of the strip, at right angles to the direction of rolling.

92. Effect of Heat Treatment in a Magnetic Field on the Permeability of Iron-nickel Alloys.—By cooling iron-nickel alloys in a magnetic field, Kelsall[492] found a marked increase of maximum permeability in the direction of the field applied during

FIG. 153.—Influence of heat treatment on the maximum permeability of iron-nickel alloys. The strength of the magnetizing field during heat treatment was 16 oersteds. (*Dillinger and Bozorth.*[526])

cooling. The effect was directional, since the permeability in the transverse direction was less than one-fourteenth of that in the longitudinal direction. As an example of the magnitudes involved, the maximum permeability of a specimen of a 78.5 per cent nickel alloy cooled in the ordinary manner was 9000; when cooled from 600°C. (1110°F.) in a magnetic field it was 111,000.

That annealing in a magnetic field increases the permeability of certain magnetic materials has been known since 1913,* but

FIG. 154.—Influence of structure and of annealing treatment on the initial permeability of iron-nickel alloys. (*Plotted from data of Dahl and Pawlek.*[523])

no systematic investigation was made until recently. The first was by Dillinger and Bozorth;[515,526] some of their results are

* See "The Alloys of Iron and Silicon,"[448] p. 378.

given in Fig. 153. It appears that the highest maximum permeabilities existed in alloys containing between 65 and 70 per cent nickel, as compared with those in the vicinity of 78 per cent nickel for rapid cooling without an applied field.

As a consequence of the foregoing findings, Dahl and Pawlek[523] extended the investigation of heat treatment in a magnetic field to specimens of different structures. Other portions of the report merely confirm the results of Dillinger and Bozorth and of Kelsall. The iron-nickel alloys used contained 40, 50, 60, 65, 70, 75, 80, and 90 per cent nickel. To obtain a fiber structure, specimens were reduced 98.5 per cent by cold rolling, then annealed at 1100°C. (2010°F.). To obtain a random structure, sheet obtained by hot rolling was annealed at 750°C. (1380°F.), reduced 80 per cent by cold rolling, then annealed at 1100°C. (2010°F.). Results are summarized by Figs. 154 and 155. The data on initial permeability indicate several maxima. The first existed in the vicinity of 50 per cent nickel and appeared for all specimens except the one with fiber structure that had been cooled in a transverse magnetic field. The second existed in the vicinity of 70 per cent nickel and was especially conspicuous for specimens cooled in a longitudinal magnetic field. The third was observed for alloys containing about 80 per cent nickel which had been cooled with no applied field. Excepting the 65 and 70 per cent nickel alloys, none of the foregoing treatments yielded an initial permeability so large as that consisting of air quenching with no applied field. For the excepted alloys having fiber structure, relatively high initial permeabilities could be obtained by cooling in a longitudinal field.

The data on maximum permeability show a definite maximum in the vicinity of 70 per cent nickel for specimens cooled in a longitudinal field. Of interest also are the data on the 50 per cent nickel alloy, because they show greater maximum permeability for the fiber-structure than for the random-structure specimens. Other data included in Fig. 155 show that the highest maximum permeability obtainable without heat treatment in a magnetic field (by air quenching) occurs in the vicinity of 80 per cent nickel; these data thus confirm those of Fig. 153.

93. Explanations of High-permeability Iron-nickel Alloys.— There is still lack of agreement on the interpretation of the magnetic properties of iron-nickel alloys; however, it may be of

interest to review briefly various ideas that have been advanced. These date from 1926, when McKeehan[237] stated that the prop-
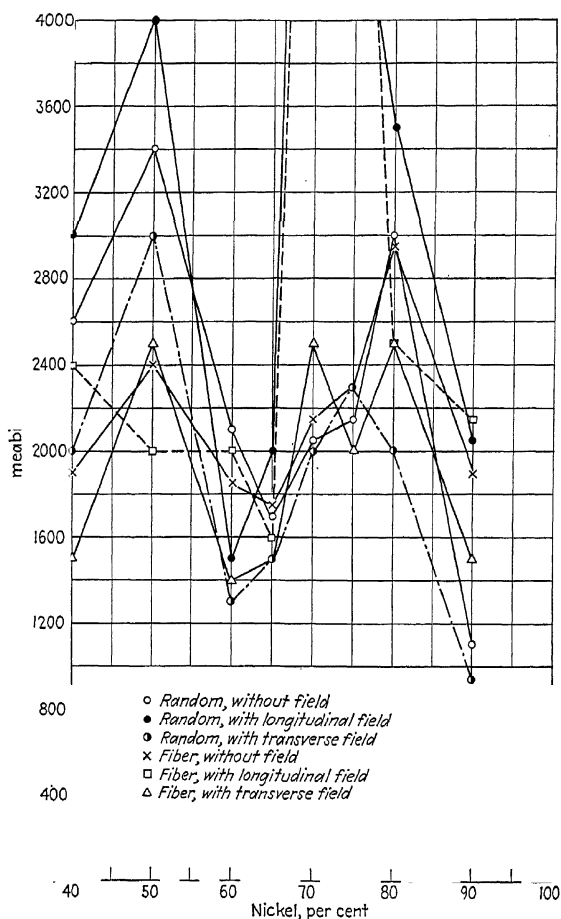

FIG. 155.—Influence of structure and of annealing treatment on the maximum permeability of iron-nickel alloys. *(Plotted from data of Dahl and Pawlek.[523])*

erties of high-permeability alloys are "now to be viewed as a direct consequence of the cancellation of magnetostriction." This explanation was not wholly convincing. Gumlich, Stein-

haus, Kussmann, and Scharnow[276] two years later suggested the existence of two compounds, *viz.*, FeNi (51.2 per cent nickel) and $FeNi_4$ (80.8 per cent nickel) or $FeNi_3$ (75.9 per cent nickel). It was assumed that FeNi persisted despite heat treatment, and that $FeNi_4$ or $FeNi_3$ could be retained only by rapid cooling, but the existence of these compounds could not be established. An explanation based upon difference of grain size likewise was found to be unsatisfactory. Honda[343] suggested the preservation of a state of high permeability existing immediately below the magnetic-inversion temperature.

The first explanation that could be considered satisfactory in its essentials was advanced by Lichtenberger;[421] it resulted from his observation that the composition having the highest permeability known in 1932 (in the neighborhood of 78 per cent nickel) did not correspond with the composition of isotropic magnetization* (71 per cent nickel, according to Lichtenberger), with that of minimum average (polycrystalline) magnetostriction (about 83 per cent nickel), or with that of isotropic magnetostriction (85.5 per cent nickel). Lichtenberger concluded, therefore, that the composition of highest permeability corresponded with that of most favorable location among the three distinguishing points. In this connection, ideas of Bozorth† on heat treatment in a magnetic field are of interest. He stated that such treatment should be most effective when the anisotropy constant is so small that small magnetostrictive strains can compete with the crystal forces in aligning the magnetization of the domains. Thus, when the constant is sufficiently small, heat treatment in a magnetic field produces high permeability, not only because the domains are stabilized in the [100] direction nearest to that of the applied field, but also because there is a tendency for the domains to be aligned by stress even more nearly parallel to the field. Diffusion or plastic flow relieves the magnetostrictive strains, consequently the domains tend to retain their new positions upon cooling, because the crystal forces are not strong enough to dominate the magnetostrictive strains that arise as soon as the domain is rotated.

The foregoing somewhat revises Bozorth's earlier views, which are quoted at length in the next section; this is necessary

* Ferromagnetic anisotropy is discussed on p. 238.
† Communication to J. L. Snoek, Nov. 22, 1935.

in order to understand the full meaning of the contributions of other workers.

94. Heat Treatment of Magnetic Materials in Magnetic Fields. According to Bozorth[476] current theory postulates that, as a ferromagnetic material cools through the magnetic-inversion point, in the absence of an external field, each elementary domain

Fig. 156.—Schematic shapes of domains as influenced by heat treatment. *(Bozorth.[476])*

(c)-Annealed below magnetic inversion

(b)-Just below magnetic inversion, or rapidly cooled

magi sion

(f)-*H* applied after rapid cooling

(e)-*H* applied to (c), Process 2

(d)-*H* applied to (c), Process 1

becomes spontaneously magnetized to saturation in a definite crystallographic direction. (For a 65 per cent nickel alloy, this is one of the cube edges, *i.e.*, a [100] direction.) As magnetization progresses, magnetostrictive stresses develop which tend to change the shape of the elementary domains. For a 65 per cent nickel alloy, the tendency is to elongate in the direction of magnetization and to contract in the direction perpendicular

to the direction of magnetization. This may be illustrated schematically as shown in Fig. 156a. This represents a part of the material above the magnetic inversion which is to become part of a single domain. As it cools through the inversion temperature, the domain becomes ferromagnetic and is saturated in some direction such as is shown in Fig. 156b. It also tends to change its shape because of magnetostriction, as is shown by the exaggerated ellipse. If the domain were free in space, the elliptic form would be taken at once; actually, it is surrounded by other domains that prevent the change of shape. If, however, the specimen is held at a sufficiently high temperature, but below the inversion temperature, for a sufficient time, the sphere will actually assume the shape shown in Fig. 156c by plastic flow of the surrounding domains. It is the hypothesis of such plastic flow that is fundamental in the theory proposed. The direction of magnetization in each domain is parallel to a crystallographic axis [100], but the domains will be oriented at random. When an external field is applied, the magnetization of the specimen as a whole is changed in three ways:

1. Magnetization of some of the domains will be reversed (180-deg. change).

2. Change of 90 deg. of magnetization of some other domains (to a different [100] direction).

3. Rotation of the magnetization vector out of a [100] direction. The third process takes place to a considerable extent only in relatively strong fields, so need be of no concern here.

Process 1 is represented by the change from Fig. 156c to 156d. It occurs with a minimum energy loss, because magnetostrictive strain is independent of the sign of magnetization, hence, the shape of the domain remains unchanged.

Process 2, Fig. 156c to 156e, requires work to be done against elastic forces. The additional energy of process 2 over process 1 seems to be the reason for the experimentally observed more frequent occurrence of process 1.

The greater the proportion of process 1 the less the energy loss accompanying magnetization to saturation; hence, the higher the maximum permeability.   An increase in proportion of process 1 is attained by heat treating in a magnetic field, for all regions are magnetized in the [100] directions nearest to the direction of the field and are stabilized there by plastic flow.   When the material

is demagnetized at room temperature, half of the regions reverse; when it is magnetized in the same (or opposite) direction, as in heat treatment, reversals again occur with a minimum loss of energy. The expectation that a perpendicular field would set up strains, consequently lower permeability, is realized, for ratios of permeabilities as high as 200 to 1 were found. The perpendicular magnetization is illustrated by Fig. 156e.

If the material is *cooled rapidly* enough from some temperature above the inversion to some temperature below the "recrystallization" temperature, there will not be time enough for the domain to change its shape as shown by Figs. 156a to 156c; hence, magnetostrictive stress will persist at room temperature, as shown by Fig. 156b. When a field is applied and the direction of magnetization changes by 90 deg. (Fig. 156f), the elastic strains set up will have a different direction from that which they had before magnetization, but the magnitude is unchanged. Consequently, the energy loss will be less than for the change from Fig. 156c to 156e, for slowly cooled material. As a result, $\mu_{max.}$ is higher for rapidly cooled than slowly cooled alloys, for cooling in the absence of external field. The highest permeability, however, is attained by heat treating in a magnetic field. The three treatments and their results may be illustrated by Fig. 153, page 212.

Now consider whether the magnitude of the magnetostrictive strain $\Delta l/l$ is adequate to change the magnetic properties as much as the several heat treatments are observed to change them.

Using 2×10^{-5} for $\Delta l/l$ for the 65 per cent nickel alloy and 28.5×10^6 lb. per sq. in. for the modulus of elasticity, it is found that about 570 lb. per sq. in. tension produces the same strain as saturation magnetostriction. Application of this stress to a slowly cooled specimen increased $\mu_{max.}$ from 7000 to 25,000— this value being higher than for rapidly cooled unstrained material.

The treatment in a magnetic field is effective only when the magnetic-inversion temperature is higher than the "recrystallization" temperature. Treatment in a field of 15 oersteds had a negligible effect on nickel, which has a low inversion temperature, and a small effect on iron, which has complicated magnetostriction and a large anisotropy constant.

95. Other Views.—Dahl and Pawlek[523] and others have raised objections to the view that heat treatment in a magnetic field is effective only when the magnetic-inversion temperature is greater than that of "recrystallization," and magnetostriction is small. They argued that if this were true, marked effect should have been found in certain of their iron-rich alloys, *e.g.*, 6 per cent silicon, 8 per cent nickel, and 10 per cent cobalt. No such effect was found. They concluded, therefore, that Bozorth's (first) explanation was inadequate, unless the mutual effect of magneto-striction and crystal forces were somehow operative.

Dahl and his coworkers[409,444] have sought an explanation on an entirely different basis, *viz.*, superstructure. Such an ordered arrangement of atoms would be difficult to detect and has never been detected by positive test. They interpreted their resistivity data to indicate superstructure, however.

The possible existence of superstructure may or may not have significance for the problem at hand. Most workers seem inclined to a view more or less in accord with that of Bozorth. Lichtenberger's might be placed in this category. Snoek[581] definitely considers high permeability to be associated with the effect of magnetostriction and the magnetic anisotropy constants.

D. COERCIVE FORCE AND RESIDUAL INDUCTION

Ferromagnetic materials are characterized by the fact that their induction does not ordinarily decline to zero when the external field strength is reduced to zero. That remaining is called "residual induction" (B_r). The coercive force (H_c) is the value of the reverse field necessary to reduce the induction to zero. The values of these quantities are usually required to be as small as is obtainable in applications taking advantage of the inherent capabilities of iron-nickel alloys. In general, coercive force is increased by cold work and decreased by annealing. Residual induction is likewise dependent upon structure, mechanical treatment, and thermal treatment. In addition, both coercive force and residual induction depend upon the field strength previously applied. In the following discussion it is usually assumed that this field strength has been so great that further increase would result in no change of coercive force or residual induction.

96. The Coercive Force of Iron-nickel Alloys.—Data on coercive force as a function of composition are summarized in Fig. 157. Earlier data by Burgess and Aston[81] are not included, because their values are. unquestionably high. Yensen's[157] data, mostly for a maximum induction of 10 kilogausses, indicate that the coercive force of irreversible alloys is increased rapidly

FIG. 157.—Coercive force of iron-nickel alloys.

by increased nickel content. So far as the reversible alloys are concerned, there seems to be little doubt that the coercive force of those containing 40 to 90 per cent nickel is well below 0.5 oersted; the scatter of the points, however, does not permit statement on any possible irregularities of the curves. (In this connection it should be added that the full-circle points credited to Gumlich, Steinhaus, Kussmann, and Scharnow[276] were taken

from their smoothed curve.)   The data of Kussmann and Schar-
now[307] are few, but they confirm the rise of coercive force as
the nickel content is increased beyond 90 per cent.   The lowest
values shown were obtained by Gumlich, Steinhaus, Kussmann,
and Scharnow[276] on high-purity alloys.   These data indicate
a flat minimum of the curve at about 0.05 oersted and 60 to 80
per cent nickel.   Even this value is high compared with what
has been obtained with special treatment of laboratory materials.
For example, Elmen[527] quoted a value, obtained by Cioffi,
of 0.03 oersted for ingot iron, 0.0145 for a 45 per cent nickel
alloy, and 0.0153 for a 78.5 per cent nickel alloy; Dillinger and
Bozorth[526] found a coercive force of 0.012 for a 65 per cent
nickel alloy.

The effect of heat treatment on coercive force was investigated
also by Gumlich, Steinhaus, Kussmann, and Scharnow.[276]
Unfortunately, alloy compositions were not given; however,
several facts are indicated.   One is that the coercive force is
reduced by rapid cooling; another is that it is reduced by a
preliminary annealing treatment.   That found most effective
by Gumlich and his coworkers was heating at 1050°C. (1920°F.)
for some hours.*   The usefulness of rapid cooling from 600°C.
(1110°F.) was verified in subsequent work by these investi-
gators;[341] the coercive forces of a 75 and a 79 per cent nickel
alloy were about halved by rapid cooling, as compared with the
values for slow cooling.

The effect of reheating on the coercive force of quenched iron-
nickel alloys was investigated by Kussmann, Scharnow, and
Steinhaus,[458] who found the alloys in the immediate vicinity of
79 per cent nickel to be most susceptible to change.   Data for a
tempering time of 14 hr. were replotted from the original curves
and are shown in Fig. 158.   The curves of equal change are
not entirely satisfactory in that the data are too few to make
certain their course; there is definite evidence, however, of some
sort of disturbance at about 79 per cent nickel.   Furthermore, the
greatest change of coercive force—over 300 per cent (increase)—
clearly took place in the neighborhood of this composition.

The effect of cold work is to increase coercive force; this was
demonstrated by Dahl, Pfaffenberger, and Sprung[445] for a 40

* The maximum time was stated to be 3 hr.; however, according to von
Auwers,[552] this was a misprint for 9 hr.

per cent nickel alloy of initial coercive force of about 0.5 oersted. This was increased rapidly to 7.5 oersteds by 10 per cent reduction, then nearly linearly to 12.5 oersteds at 90 per cent reduction. By suitable annealing, the coercive force of cold-worked alloys can be decreased markedly. For example, Kersten[494] annealed a 45 per cent nickel alloy that had been reduced about 97 per cent by cold rolling. Annealing for 1 hr. at temperatures ranging from 200 to 900°C. (390 to 1650°F.) reduced the coercive force

FIG. 158.—The influence of tempering for 14 hr. on the coercive force of quenched iron-nickel alloys, expressed as percentage change. (*Plotted from data of Kussmann, Scharnow, and Steinhaus.*[458])

from 12 oersteds to 5 oersteds at 500°C. (930°F.); a sharp drop began at about 550°C. (1020°F.) which was complete at about 700°C. (1290°F.), for which temperature the coercive force was only a fraction of an oersted. A similar result was obtained by Pawlek[537] for a 40 per cent nickel alloy. The coercive force after 80 per cent reduction by cold work was about 8.5 oersteds; this was reduced to 6 oersteds by annealing temperatures up to 500°C. (930°F.) at which temperature the value dropped abruptly to less than 2 oersteds. Still higher annealing temperatures brought about a further reduction to less than 1 oersted. After a reduction of 98.5 per cent, the coercive force was about 12 oersteds. This was reduced to about 9 oersteds after annealing

at 400°C. (750°F.) and the value dropped rapidly to about 2 oersteds after annealing at 500°C.; this was followed by a regular decline to less than 1 oersted after annealing at 600°C. (1110°F.). The crystallographic changes as a result of these treatments are described elsewhere (page 208). The influence of temperature on the coercive force of two irreversible alloys containing 5 and 10 per cent nickel was reported by Kühlewein.[420] The results show no great change up to 400°C. (750°F.), then follows a rapid decline of value with further increase of temperature. As was to be expected, hysteresis was marked in the 10 per cent nickel alloy.

According to Buckley and McKeehan,[209] tension decreases the coercive force of alloys containing less than 81 per cent nickel and increases it slightly in those containing more than 81 per cent nickel. Preisach[317] found this decrease in a hard 8 per cent nickel alloy of initial coercive force of about 17 oersteds; increased tension caused decreasingly rapid decline and the original curve indicates a limiting value of about 8 oersteds for tension in the vicinity of 9000 kg. per sq. cm. (128,000 lb. per sq. in.). The decrease found by von Auwers[330] upon stressing up to 7 to 14 kg. per sq. mm. (10,000 to 20,000 lb. per sq. in.) alloys containing 36, 40, 46, and 60 per cent nickel was less marked. Other data, on a 78.5 per cent nickel alloy, were given also by Preisach.[427]

The effect of hydrostatic pressure up to 1000 kg. per sq. cm. (14,200 lb. per sq. in.) on the coercive force of two alloys containing 40 and 46 per cent nickel was determined by von Auwers.[330] Little change occurred upon the application of pressure up to 500 kg. per sq. cm. (7100 lb. per sq. in.). Further application of pressure caused an increase of coercive force, and the effect was the more pronounced in the 40 per cent nickel alloy.

Cooling an iron-nickel alloy in a magnetic field decreases the coercive force of the alloy, judging by an experiment by Bozorth and Dillinger[515] on a 65 per cent nickel alloy. Other results on the effect of a magnetic field applied during heat treatment were reported by Dahl and Pawlek;[523] the effect of fiber structure was investigated simultaneously, consequently it is convenient to review these effects together. Eight alloys containing 40 to 90 per cent nickel were prepared from charcoal iron and shot nickel; differences from results on high-purity alloys are therefore

to be expected. The ingots were reduced to 0.3-mm. sheet in two ways: (1) To obtain a random structure, the forgings were hot rolled to 1.5-mm. sheet, annealed at 750°C. (1380°F.), cold rolled to 0.3 mm., then annealed at 1100°C. (2010°F.). (2) To obtain fiber structure, the ingots were cold rolled to 0.3-mm.

FIG. 159.—The coercive force of iron-nickel alloys after various treatments: *A*, cooling slowly; *B*, cooling slowly in a longitudinal magnetic field; *C*, cooling slowly in a transverse magnetic field.   (*Dahl and Pawlek.*[523])

sheet, then annealed at 1100°C. (2010°F.). Results for the several treatments and structures are summarized in Fig. 159. It is to be seen that the lowering of coercive force by cooling in a magnetic field was especially effective in the 75 and 80 per cent nickel alloys. The reduction was about the same as is caused by rapid cooling (as compared with slow cooling).

97. The Residual Induction of Iron-nickel Alloys.—Perhaps the best picture of the variation of residual induction with concentration of ordinary iron-nickel alloys is afforded by the data of Yensen[157] (Fig. 160). The values are shown to decline rapidly in the irreversible region as the nickel content is increased. In the reversible region a maximum in the neighborhood of 50 per cent nickel is indicated. As isolated from other properties, however, such information is of little meaning.

FIG. 160.—Residual induction of iron-nickel alloys for a maximum induction of 10 kilogausses. (*Yensen.*[157])

The residual induction of iron-nickel alloys is highly dependent upon the structure produced by mechanical treatment, heat treatment, or both. This was shown by Dahl and Pawlek[523] who tested alloys prepared from charcoal iron and shot nickel by melting in an induction furnace. Specimens with random and with fiber structure were tested after several heat treatments, including cooling in longitudinal and transverse magnetic fields. Results are summarized in Fig. 161, in which residual magnetization is shown in ratio to saturation magnetization. Alloys in the vicinity of 50 and 80 per cent nickel appear to have been most

susceptible to treatment; those in the 60 to 70 per cent nickel range were relatively unsusceptible.

Other data on residual induction as a function of composition were supplied by Burgess and Aston.[81]   Gumlich[214] reported values for 50 and 78 per cent nickel alloys that were higher than corresponding values of Yensen[157] but lower than those of Dahl

Fig. 161.—The influence of structure and of annealing treatment on the residual induction of iron-nickel alloys, expressed as the ratio of residual magnetization to saturation magnetization.   (*Plotted from data of Dahl and Pawlek.*[523])

and Pawlek.[523]   This fact is merely a further example of the erratic results to be expected of certain ordinary magnetic measurements.

The effect of annealing on cold-worked alloys containing 45 per cent nickel was investigated by Kersten.[494]   The ratio of residual magnetization to saturation magnetization remained constant (about 0.45) for annealing temperatures to about 350°C. (660°F.), then increased to about 0.7 at 600°C. (1110°F.).   With further increase of annealing temperature, the ratio decreased rapidly.

More detailed information on the effect of annealing on cold-worked alloys of iron and nickel was given by Pawlek[537] and by

Dahl and Pawlek.[557]   This information alone is of no considerable interest, consequently reference is made to the discussion on pages 208 *ff*.   The effect of (testing) temperature on the residual induction of two irreversible alloys, containing 5 and 10 per cent nickel, was reported by Kühlewein.[420]   Residual induction increased with temperature to a maximum in the vicinity of the magnetic-inversion temperature, then declined rapidly.   Measurements upon cooling showed the effect to be irreversible. The form of the curves for these alloys differed from that of iron and that of nickel.

According to von Auwers[330] the effect of hydrostatic pressure [up to 1000 kg. per sq. cm. (14,200 lb. per sq. in.)] was observable in his experiments in alloys containing 40, 46, and 60 per cent nickel, but not in those containing 36 and 78 per cent nickel. The effect was most marked in the 40 per cent nickel alloy; the highest pressure applied more than doubled the initial residual induction.   Von Auwers also investigated the effect of tension on the alloys containing 36, 40, 46, and 60 per cent nickel.   The effect was invariably to increase the residual induction; *e.g.*, the application of a tensile load of 10 kg. per sq. mm. (14,200 lb. per sq. in.) to the 40 per cent nickel specimen increased the initial value of 4 kilogausses to 7.5 kilogausses.   It is supposed that the effect of tension is to increase residual induction when saturation magnetostriction is positive and to decrease it when magnetostriction is negative; this was demonstrated by Buckley and McKeehan.[209]

E. CYCLIC ENERGY LOSSES

Under ordinary conditions, energy is invariably lost when a ferromagnetic substance undergoes a cycle of magnetization. The hysteresis loss is given by the area of the hysteresis loop or

$$W_h = \frac{1}{4\pi} \oint H dB$$

The simplest way of evaluating the integral is by the use of a planimeter; the area of the loop in units of gauss-oersteds, when divided by 4π, yields hysteresis loss in ergs per cubic centimeter per cycle.   For a given frequency this may be converted to watts per kilogram by multiplying by $10^{-4}f/d$, where f is the frequency and d is the density of the material.

In an alternating field—or more exactly, in any changing field—energy is lost through eddy currents. Eddy-current loss depends upon the form of the core, the frequency, and other factors. For sheet material it has been shown that eddy-current loss in ergs per cubic centimeter is given to a first approximation by

$$W_e = \frac{\pi^2 t^2 f^2 B^2_{\text{max}}}{6\rho \times 10^3}.$$

where t is the sheet thickness in centimeters, f is the frequency, B_{max} is the maximum induction, and ρ is the electric resistivity in

FIG. 162.—Hysteresis loss of iron-nickel alloys for a maximum induction of 10 kilogausses. (*Yensen.*[157])

microhm-centimeters. For the limitations of this relationship, see the standard texts.

The discussion to follow is divided into two parts; one is devoted to losses at high inductions, as in "power" apparatus, the other to those at low inductions, as in certain equipment used by the communication industry.

98. Core Losses at High Inductions of Iron-nickel Alloys.— The way in which the hysteresis loss at high inductions of iron-nickel alloys varies with composition is shown by the data of Yensen[157] given in Fig. 162 and of Elmen.[297] Hysteresis loss increases with increased nickel content in the alpha-phase range, attains maximum value in the two-phase range, and is relatively

low in the gamma-phase range, then rises as 100 per cent nickel is approached. The same trends were found by Broniewski and Smolinski.[443] Such factors as impurity content and physical condition have marked effect on hysteresis loss for a given nickel content and maximum induction. As an example, the following data, given by Yensen,[438] may be cited: Before 1924, the smallest loss obtainable for iron-nickel alloys containing 50 per cent nickel for inductions approaching saturation was about 1000 ergs per cu. cm. per cycle. In 1924, this was reduced to 400 or less; by 1932, values of 200 or less were common, and in some instances the loss was less than 100 ergs. Dillinger and Bozorth[526] found a loss of only 50 ergs in one instance, with an alloy containing 65 per cent nickel.

TABLE 34.—ENERGY LOSS OF LOW-NICKEL IRON-NICKEL ALLOYS [SHEETS 0.15 MM. (0.006 IN.) THICK, ANNEALED 4 HR. AT 900°C. (1650°F.)]*

Nickel, per cent	Hysteresis loss at 10 kilo-gausses and 50 cycles, watts per kg.	Total loss at 10 kilo-gausses and 50 cycles, watts per kg.
0†	0.70	1.20
0.27	0.62	1.18
1.50	....	1.24
2.8	1.25	1.54
2.9	....	1.60
5.0	....	2.02

* Dahl, Pawlek, and Pfaffenberger.[524]
† Electrolytic iron.

Core losses of alpha-phase alloys prepared from electrolytic materials, determined by Dahl, Pawlek, and Pfaffenberger,[524] are given in Table 34. The 0.15-mm. (0.006-in.) sheets were annealed 4 hr. at 900°C. (1650°F.) in hydrogen before testing. The hysteresis loss shown for electrolytic iron—0.70 watt per kg., or about 1100 ergs per cu. cm. per cycle—agrees well with other data on similar material similarly treated, consequently it is likely that the data of Table 34 are representative of low-nickel alloys that have not been specially purified.

The following core losses for 45 to 50 per cent nickel alloys in the form of sheet 0.01264 in. (0.32 mm.) thick were reported by Crawford and Thomas:[522]

Induction, kilogausses...........   10   14
Energy loss, watts per lb. at 60 cycles|0.004|0.013|0.06|0.2|0.33   0.48 0.63

According to the National Physical Laboratory[220] the hysteresis loss in ergs per cubic centimeter per cycle of 78.5 per cent nickel iron-nickel alloys is given by $W_h = 0.00014B^{1.56}$.

99. Thermal and Mechanical Effects.—The only data on the variation of hysteresis loss with temperature were determined by Kühlewein[420] on a 5 per cent nickel alloy at a frequency of 50 cycles and a field strength of 8 oersteds; they are subjoined:

Temperature,°C.	20	164	588	733	811	770	656
Temperature,°F.	68	327	1090	1351	1492	1418	1213
Hysteresis loss, watts per kg.	2.96	2.57	2.95	2.03	1.04	0.04*	0.83*

* Partly gamma phase; retained upon cooling.

The effect of tension on the hysteresis loss of five iron-nickel alloys was investigated by Aizawa and Wachi;[439] their results are quoted in Table 35. The loss appears to have been minimum for an intermediate value of tension for the 50 to 80 per cent nickel alloys.

Hagemann and Hiemenz[449] investigated the effect of sheet thickness, annealing atmosphere, and separating material (magnesia, sand, lime, carborundum, alumina, and paper) on the energy loss of an alloy containing 47 per cent nickel and 1 per cent manganese. Results are given in Table 36; they seem to be too erratic to support definite conclusions.

Yensen[438] investigated the effect of rolling and of subsequent annealing on the hysteresis loss at 10 kilogausses and 60 cycles of vacuum-melted 50 per cent nickel alloys. No marked change was noted for reductions up to about 90 per cent for vacuum-annealed alloys. Heavier reductions were accompanied by rapid increase of hysteresis loss. Hydrogen annealing caused smaller losses for all reductions, with the minimum value appearing for about 92 per cent reduction in thickness.

100. Effect of Frequency on Hysteresis Loss at High Inductions.—The effect of frequency on the hysteresis loss at 5 to 7 kilogausses for a 50 per cent nickel iron-nickel alloy was investigated by Neumann.[284] Results, reproduced in Table 37,

TABLE 35.—INFLUENCE OF MECHANICAL TENSION ON HYSTERESIS LOSS OF
IRON-NICKEL ALLOYS*

Nickel, per cent	Tension, lb. per sq. in.†	Induction, kilogausses	Hysteresis loss, ergs per cu. cm. per cycle
40.05	0	10.5	2310
	2,700	10.7	2520
	15,400	10.3	2920
	26,300	9.9	3570
	39,400	8.3	3980
	51,500	7.7	7250
49.40	0	7.8	1010
	1,900	9.6	975
	4,300	10.4	813
	12,900	11.2	975
	30,700	12.6	2340
	52,800	11.8	7870
59.30	0	7.4	422
	7,000	10.0	341
	18,600	13.0	390
	28,400	14.2	471
	36,700	12.9	2015
	43,700	12.0	2730
69.5	0	6.2	207
	2,200	7.5	93
	7,000	8.6	85
	19,100	10.0	126
	30,500	10.4	618
	43,000	9.8	1770
	51,900	9.6	2110
79.6	0	9.5	179
	1,100	8.5	89
	6,500	8.5	81
	17,200	8.5	162
	29,700	8.0	382
	43,200	8.0	796

* Aizawa and Wachi.[439]
† The larger tensions appear to have exceeded the elastic limit.

indicate that the loss was increased by about 20 per cent at 500 cycles, and by 60 per cent at 1500 cycles. Guye and Schidlof,[57] however, concluded, in agreement with the general opinion, that frequency has no effect in the 100 to 1200 cycle range for alloys containing 27 to 45 per cent nickel and appreciable carbon. It is to be concluded, therefore, that Neumann's results include at least some eddy-current loss.

101. Core Losses at Low Inductions.—The communication industries are often more interested in the magnetic behavior of materials at low inductions than at high inductions. This has given rise to extensive analysis of core losses for maximum inductions of 100 gausses or less. Jordan,[201] for example, concluded that a third kind of loss exists which he called *Nachwirkung*. Others use such terms as viscosity, magnetic hysteresis, square law hysteresis or, noncommittally, residual loss. Residual loss is assumed to be proportional to the square of the maximum induction applied cyclically; it has been the subject of considerable controversy on origin and even existence.

TABLE 36.—CORE LOSS (AT 5 KILOGAUSSES AND 50 CYCLES, IN WATTS PER KG.) OF VARIOUSLY TREATED STRIPS OF ALLOY CONTAINING 47 PER CENT NICKEL AND 1 PER CENT MANGANESE*

Separating material	Annealed in vacuum		Annealed in hydrogen		Annealed in nitrogen		Annealed in air	
	Thickness, mm. (0.004 and 0.0008 in.)							
	0.1	0.02	0.1	0.02	0.1	0.02	0.1	0.02
Magnesia......	0.28	0.48	0.27	0.47	0.29	1.28	0.25	0.31
Sand..........	0.28	0.55	0.26	0.45	0.31	1.30	0.27	0.37
Lime..........	0.32	0.48	0.30	0.21	0.35	0.48	0.32	0.64
Carborundum..	0.32	0.73	0.28	0.51	0.40	1.22	0.32	1.00
Alumina.......	0.28	0.68	0 28	0.53	0.28	1.35	0.25	0.39
Paper..........	0.28	0.50	0.28	0.21	0.26	0.26	0.27	0.37

* Hagemann and Hiemenz.[449]

The theory of core losses at low inductions is based on the Rayleigh[8] hysteresis loop. Its development was given recently by Legg[569] who summarized the basic relations between the magnetic characteristics of the core of a coil and the inductance

TABLE 37.—EFFECT OF FREQUENCY ON THE ENERGY LOSS OF A 50 PER CENT NICKEL IRON-NICKEL ALLOY*

Maximum induction, gausses	Hysteresis loss, ergs per cu. cm. per cycle, at a frequency of		
	0 cycles	490 cycles	1470 cycles
5136	161	193	
5270	169	. . .	266
6680	277	343	
6730	281	. . .	454

* Neumann.[284]

and resistance of the coil as measured by the alternating-current bridge. The several loss terms are defined by

$$\frac{R_f}{\mu_{max.} f L_f} = aB_{max.} + ef + c = \frac{8\pi W}{B^2_{max.}}$$

where R_f is the difference between alternating- and direct-current resistance of a toroidal coil of inductance L_f due to the core material of permeability $\mu_{max.}$, when maximum induction in gausses is $\pm B_{max.}$ and the frequency is f cycles per sec. The hysteresis coefficient is a, the eddy-current coefficient is e, and the residual loss term is c. W is energy loss in ergs per cubic centimeter per cycle. The coefficient a is directly related to hysteresis loss; *i.e.*,

$$aB^3_{max.} = 8\pi W_h$$

This is not so directly true of the hysteresis constant h proposed by Jordan which is based on a magnetizing force given in ampere turns per centimeter and a frequency of approximately 800 cycles ($\omega = 5000$, where $\omega = 2\pi f$). The following relationships exist between Legg's a and Jordan's h:

$$a = \frac{704h \times 10^{-6}}{\mu^2}$$

Legg's eddy-current coefficient e is related to Jordan's w by

$$e = \frac{1580w \times 10^{-9}}{}$$

and his residual loss term c to Jordan's n by

$$c = \frac{1260n \times 10^{-6}}{}$$

A still different set of coefficients, also based on a magnetizing force in terms of ampere turns per centimeter, but a frequency of 1000 cycles, was proposed by Weis;[548] whether or not they will entirely supplant those of Jordan in Germany is not known. The following are the relationships between a, e, and c and the coefficients h, w, and n of Weis:

$$\sim \; = \; \frac{5.627h \times 10^{-4}}{\mu^{z}}$$
$$e = \frac{w \times 10^{-6}}{\mu}$$
$$c = \frac{n \times 10^{-3}}{}$$

102. Hysteresis Loss at Low Inductions of Iron-nickel Alloys. Hysteresis coefficients of some iron-nickel alloys in several physical conditions, determined by Ellwood and Legg,[594] are given in Table 38. The value for the 81 per cent nickel

TABLE 38.—ENERGY LOSSES AT LOW INDUCTIONS OF IRON-NICKEL ALLOYS*

Nickel, per cent	Condition	Initial permeability	Hysteresis coefficient, $a \times 10^6$
0	Compressed powder	35	50
81	Compressed powder	75	5.5
35	Laminated, annealed	1660	5.0
38	Laminated, hard	100	9.6
38	Laminated, annealed	1330	1.5
40	Laminated, annealed	2060	1.4
45	Laminated, annealed	2550	0.43
78.5	Laminated, annealed	3900	0.6

* Ellwood and Legg.[594]

alloy in the form of compressed powder is considerably smaller than that reported earlier by Shackelton and Barber[288] for alloys containing 78.5 per cent nickel, and by Spooner[246] for those containing 50 per cent nickel. A laboratory specimen of a

35 per cent nickel alloy tested by Ellwood and Legg yielded a coefficient of about 2.5×10^{-6}, as compared with a value of 5.0×10^{-6} obtained for a less carefully prepared alloy of the same nickel content. This is consistent with the usual observation that hysteresis loss tends to become smaller as alloy purity and heat treatment are improved. It was found also that the hysteresis coefficient was practically constant over the low-induction range for all frequencies.

Fig. 163.—Hysteresis-loop coefficient of variously treated iron-nickel alloys after 90 per cent reduction by cold rolling. Preliminary treatment consisted of annealing under hydrogen for 2 hr. at 950 to 1000°C. (1740 to 1830°F.). (*Computed from data of Dahl, Pfaffenberger, and Sprung.*[445])

103. Effect of Cold Rolling on Hysteresis Loss at Low Inductions.—Dahl, Pfaffenberger, and Sprung[445] determined the hysteresis loss of a series of iron-nickel alloys after several treatments. Sheets were annealed 2 hr. at 950 to 1000°C. (1740 to 1830°F.) in hydrogen, then air cooled, furnace cooled, or water quenched. Specimens were then subjected to 90 per cent reduction by cold rolling. Results are given in Fig. 163 (the hysteresis coefficients have been computed from the original data, which are in terms of Jordan's hysteresis constant). The thermal history of the material before cold rolling is seemingly of little consequence. It also appears that cold rolling has the greatest effect

on hysteresis loss in the composition range in which heat treatment has great effect on magnetic properties. The effect of degree of reduction by cold rolling on a 40 per cent nickel alloy is shown by Fig. 164. It is to be seen that the sharpest increase of hysteresis loss accompanies the initial stage of cold work. A different alloy must have been used for this experiment, judging from the fact that at 90 per cent reduction the hysteresis coefficient was about 43×10^{-6} as compared with a value of about

FIG. 164.—The effect of cold rolling on the hysteresis-loop coefficient of a 40 per cent nickel iron-nickel alloy. (*Computed from data of Dahl, Pfaffenberger, and Sprung.*[445])

10×10^{-6} shown by Fig. 163 for a composition of 40 per cent nickel.

104. Residual-loss Term of Iron-nickel Alloys.—The excess core loss at low inductions has been investigated recently by Seyffert[611] as well as by Ellwood and Legg.[594] Results are compared in Fig. 165. Perhaps the most notable feature of these data is the large values for hard-rolled alloys as compared with annealed alloys. It is noteworthy also that residual losses found by Ellwood and Legg were invariably smaller than those of Seyffert. It may be concluded provisionally, therefore, that residual loss is decreased by increased purity of the material and by careful annealing.

Analysis of the loss of a 35 per cent nickel alloy by Ellwood and Legg indicated increase with frequency up to about 500 cycles, and constancy of value at higher frequencies (to at least 10,000 cycles).

The very small residual loss of some materials, *e.g.*, annealed 78.5 per cent nickel alloys, led Ellwood and Legg to suggest that such loss may be caused by elastic hysteresis or perhaps simple mechanical friction, with magnetostriction as the coupler between elastic or frictional quantities and the magnetizing field. Thus work is expended by the alternately contracting and

Fig. 165.—The residual-loss term at low inductions of iron-nickel alloys.

expanding core, in addition to eddy-current and magnetic-hysteresis loss. Whether such an explanation is adequate remains to be seen.

F. DIRECTIONAL FERROMAGNETIC PROPERTIES

It is a matter of experimental observation that the ease of magnetization of a crystal of a ferromagnetic substance depends upon the crystal axis selected.   In iron, for example, a cube edge (a [100] direction) is the direction of easiest magnetization, which is to say that saturation is attained in a field weaker than is required in any other direction.   Of the two remaining principal directions, magnetization is hardest along a cube diagonal (a

[111] direction) and of intermediate difficulty along a face diagonal (a [110] direction). The magnetization of nickel behaves in reverse order.

105. Theory of Anisotropy in High-strength Fields.—The subject of ferromagnetic anisotropy has been reviewed recently by Bozorth.[587] Van Vleck[615] reviewed the attempts to explain anisotropy on the basis of atomic theory and has supplied the most promising explanation to date.

In brief, it is supposed that the work required to magnetize to saturation at a given temperature and in a given direction in an unconstrained cubic crystal,

$$\int_0^{I_\infty} H dI,$$

is given by an expression in ascending powers of the direction cosines. Only the last stage of the magnetization process is accounted for, *i.e.*, that which consists of rotation of the magnetization vector out of a direction of easy magnetization into the direction of the applied field. The first three terms of the expression are:

$$W_\alpha = K_0 + K_1(\alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2 + \alpha_1^2\alpha_2^2) + K_2(\alpha_1^2\alpha_2^2\alpha_3^2)$$

where the α's are the direction cosines of the given direction as referred to the principal cubic axes of the crystal and the K's are constants independent of direction. For the principal directions, there exist the following relations:

$$W_{100} = K_0$$
$$W_{110} = K_0 + \frac{K_1}{4}$$
$$W_{111} = K_0 + \frac{K_1}{3} + \frac{K_2}{27}$$

The simplest way to evaluate the constants is to determine the energies in these directions from the magnetization curves, then to use the relations in the following form:

$$K_0 = W_{100}$$
$$K_1 = 4(W_{110} - W_{100})$$
$$K_2 = 27(W_{111} - W_{100}) - 36(W_{110} - W_{100})$$

If K_2 is neglected, the sign of K_1 determines whether the direction of easy magnetization is [100] or [111] and the order is always [100], [110], [111], or the reverse. That this order is not always followed was demonstrated by Bozorth,[554] for if K_1 is small compared with K_2, and is of opposite sign, the direction of easiest magnetization may be [110].

Ferromagnetic anisotropy exists also in low-strength fields, but the theory as yet is unsatisfactory, possibly excepting the case of a field strength of zero.

106. Ferromagnetic Anisotropy of Iron-nickel Alloys.—Of the several reports on the ferromagnetic anisotropy of iron-nickel

FIG. 166.—Energy differences of iron-nickel alloys.   (*Kleis.*[568])

alloys, that of Kleis[568] probably provides the most accurate information. The specimens contained about 0.15 per cent of impurities, mainly sulphur, silicon, and cobalt. Single crystals were cut into oblate spheroids; measurements on them permitted the plotting of *I-H* curves from which the anisotropy constants of Table 39 were computed. The most unexpected result was that the direction of most difficult magnetization changed, not from [100] to [111] as the iron content was increased beyond a critical amount, but from [100] to [110]. The transition, indicated somewhat roughly by the data shown in Fig. 166, occurred at 76 per cent nickel. This order of directions persisted at 50 per

cent nickel, the lowest nickel content investigated. It was found also that the value of the demagnetizing factor N decreased with increased temperature; this made the computation of K_0 uncertain, consequently this constant is not given in the table.

The first worker to investigate the anisotropy of iron-nickel alloys was Lichtenberger,[421] who used Akulov's "orientation factor," page 323, which assumes that the K_2 term is negligible. Although Lichtenberger's data were incomplete, he concluded that the transition of direction of easiest magnetization takes place at 71 per cent nickel. Another estimate of the position of the transition was made by Burgers and Snoek[517] and by Snoek;[581] the value arrived at is 66 per cent nickel. Thus, there is considerable scatter among the reported values. However, recent and more accurate experiments indicate that at room temperature $K_1 = 0$ at 74 ± 1 per cent nickel.*

TABLE 39.—ANISOTROPY CONSTANTS OF SOME IRON-NICKEL ALLOYS*

Nominal nickel, per cent	Temperature, °C.	Anisotropy constant, ergs per cu. cm. $\times 10^{-3}$	
		K_1	K_2
100	20	−34	50
	200	5.0	20
90	20	−7.0	−23
	200	−2.0	−10
70	20	6.8	−17
	200	1.5	−4
65	20	15	−70
	200	12	−40
50	20	33	−180
	200	25	−80

* Kleis,[563] summarized by McKeehan.[601]

G. AUTHOR'S SUMMARY

1. At ordinary temperature the saturation magnetization of alpha-phase iron-nickel alloys is little changed by variation of nickel content. In the gamma-phase range, saturation magnetization increases from a low value at about 30 per cent nickel to a maximum of about 16,000 gausses at 47 to 48 per cent nickel, then declines approximately linearly to about 6000 gausses at

* H. J. Williams, private communication.

100 per cent nickel. A few data for absolute zero, obtained by extrapolation, indicate that saturation magnetization is the greater the higher is the iron content of the alloys, and is somewhat greater than rule-of-mixtures values. There is some indication of a maximum at about 10 per cent nickel.

The variation of magnetic induction with composition for various field strengths at ordinary temperature shows the same minimum near 30 per cent nickel and maximum near 50 per cent nickel as saturation magnetization. There is deviation from the shape of the saturation curve for fields of small strength.

2. As early as 1910 the permeability of certain alloys of iron and nickel was reported to be somewhat greater than that of iron, but it was not until 13 years later that data showing their many times greater permeability at low inductions were published. The best results were obtained with special heat treatment, which was effective for alloys containing about 50 to about 90 per cent nickel. The highest permeability in other alloys, such as those containing 48 to 50 per cent nickel, which have the highest saturation magnetization of the gamma-phase series, is obtained by purification treatment, such as by annealing in hydrogen. Such treatment is effective for other alloys as well, of course. Permeabilities as high as 13,000 initial and over 400,000 maximum have been reported for 78.5 per cent nickel alloys. The upper limit, however, is unknown, because the 1,000,000 mark has been passed.

3. Mechanical strain can have considerable effect on permeability. Simple tension in moderate amounts increases the permeability of alloys containing less than about 81 per cent nickel and decreases the permeability of those containing more nickel. (The direction of the effect depends upon the sign of the magnetostrictive effect.) Random strains are likely to decrease permeability.

4. Various combinations of thermal and mechanical treatment are capable of producing drastic and often useful changes of permeability. Drastic reductions by cold rolling, which produce "textures," may increase permeability in a definite direction after annealing. Another purpose of such treatment is to obtain constancy of permeability of hard alloys over a range of inductions—usually low.

5. The most spectacular increases of permeability of iron-nickel alloys (containing more than 50 per cent nickel) have been brought about by heat treatment in a magnetic field. In this way, permeabilities in the hundreds of thousands have been produced. This is true, however, only in the direction of the applied field during cooling.

6. Attempts to "explain" the high permeability of certain iron-nickel alloys have been more numerous than successful. That currently in most favor is based upon magnetostriction and the magnetic anisotropy constants. The details do not lend themselves to condensation, however.

7. The coercive force of iron-nickel alloys is minimum in the 40 to 80 per cent nickel range, for which values less than 0.05 oersted are common and for which values of 0.01 to 0.02 have been found. In general, low coercive force is favored by moderately rapid cooling and by purification of the alloy. The effect of reheating on quenched alloys is most marked in the vicinity of 79 per cent nickel; changes of as much as 300 per cent have been found after prolonged annealing. The effect of cold work is to increase coercive force. Coercive force is decreased by cooling in a magnetic field; the effect is most pronounced in the 70 to 80 per cent nickel range.

8. For maximum induction approaching saturation the residual induction of alpha-phase iron-nickel alloys declines rapidly with increased nickel content. In the gamma-phase region, residual induction is maximum in the vicinity of 50 per cent nickel. The dependence upon structure or "fibering" is high, especially for alloys containing about 50 and about 80 per cent nickel.

9. The hysteresis loss of alpha-phase iron-nickel alloys is increased rapidly with increased nickel content. That of ordinarily prepared gamma-phase alloys is relatively low in the 35 to 85 per cent nickel range. Specially prepared alloys of the high-permeability type have extraordinarily low hysteresis loss; *e.g.*, values as small as 50 ergs per cu. cm. per cycle have been reported.

Core losses at high inductions are assumed to be composed of hysteresis loss and eddy-current loss. Refined measurements at inductions of less than 100 gausses show a third component, or residual loss.

10. The direction of easiest magnetization of iron is [100]; that of nickel is [111]. Starting from nickel, as the iron content is increased, the direction of easiest magnetization remains [111] until an alloy containing about 74 per cent nickel is reached. Thereafter, the direction of easiest magnetization is [100], as in iron.

11. For alloys of standardized composition trade names are often used in the literature. For convenience, a list is subjoined, arranged in order of increasing nickel content.

Nickel, per cent	Trade name	Nickel, per cent	Trade name	Nickel, per cent	Trade name
30	Thermoperm	48	Permenorm	65	65 Permalloy
36	Hyperm 36	50	Conpernik	78.5	Mumetal
			Copernik		78.5 Permalloy
40	Hyperm 40		Hipernik		Permalloy A
			Hyperm 50		Permax
45	45 Permalloy		Isoperm		
	Permalloy B		Laminic	81	81 Permalloy
			Nicalloy		

CHAPTER VIII

MAGNETIC PROPERTIES OF COMPLEX
IRON-NICKEL ALLOYS

Magnetically Soft Alloys Excepting Those Containing Cobalt—
Magnetically Soft Alloys of Iron, Nickel, and Cobalt—The Magnetic
Properties of Structural Steels Containing Nickel—Permanent-magnet
Materials Containing Iron and Nickel—Author's Summary

The enormous volume of information on the magnetic prop-
erties of essentially binary alloys of iron and nickel, reviewed in
Chapter VII, by no means comprises the total. Study of the
useful properties of certain of the gamma-phase iron-nickel alloys
was soon followed by the discovery that still other useful prop-
erties could be produced upon addition of a third, and sometimes
of a fourth, element. There are three classes of effects on the
magnetic properties of the binary alloys caused by such additions.
(1) Additions of such elements as chromium, copper, molyb-
denum, or vanadium serve in varying degrees to reduce the
sensitivity of the alloys to heat treatment, and thus facilitate
the development of high permeability without rigorous control
of cooling rate. (2) The addition of the ferromagnetic element
cobalt produces radical modification of the permeability and
hysteresis characteristics of the high-permeability materials.
(3) Addition of such elements as aluminum and titanium causes
great magnetic hardness, consequently such alloys are important
permanent-magnet materials.

A. MAGNETICALLY SOFT ALLOYS EXCEPTING THOSE
CONTAINING COBALT

Ordinary effects of additions of non-magnetic elements to
gamma-phase iron-nickel alloys are decreased saturation magne-
tization, decreased maximum permeability, and increased electric
resistivity. Certain amounts of some addition elements increase
initial permeability. Another useful effect of some additions is
the desensitization of alloys otherwise strongly affected by heat

treatment; this is an obvious advantage, because such alloys may be manufactured to meet definite magnetic specifications without rigorous control of cooling rate.

107. Magnetic Properties of Iron-nickel Alloys Containing Chromium or Molybdenum.—Considerable investigation has been made of the effects of chromium and molybdenum on the magnetic properties of iron-nickel alloys, because both elements increase electric resistivity yet permit high initial permeability. Figure 167 shows initial permeabilities obtained by Elmen[527] on alloys containing 78.5 per cent nickel and various amounts of chromium or molybdenum. Shown also is the effect of slow cooling as compared with quenching. In quenched alloys the

Fig. 167.—The initial permeability of alloys containing 78.5 per cent nickel and variable molybdenum or chromium. (*Elmen.*[527])

highest initial permeability occurred at 2.4 per cent chromium and at 1.6 per cent molybdenum, and the chromium alloy seems to have had the higher peak of initial permeability although the difference is not significant. In slowly cooled alloys, however, 3.8 per cent molybdenum clearly produced higher initial permeability than did the corresponding amount of chromium—in this instance, also 3.8 per cent. Other properties of these alloys are given in Table 40. The electric resistivity of the

Composition, per cent		Initial permeability	Hysteresis-loop coefficient, $a \times 10^6$	Residual-loss term, $c \times 10^6$
Ni	Cr			
78	2.4	14,600	0.07	3
79	8	3,025	2.6	14

TABLE 40.—PROPERTIES OF ALLOYS CONTAINING 78.5 PER CENT NICKEL
AND 3.8 PER CENT CHROMIUM OR MOLYBDENUM*

Alloy added	Initial permeability	Maximum permeability	Hysteresis loss, ergs per cu. cm. per cycle, for saturation magnetization	Residual induction, gausses	Coercive force, oersteds	Saturation magnetization $4\pi I_\infty$, gausses
Cr	12,000	62,000	200	4,500	0.05	8,000
Mo	20,000	75,000	200	5,000	0.05	8,500

* Elmen.[527]

standard 78.5 per cent nickel alloy is roughly trebled by 3.8 per cent molybdenum and quadrupled by 3.8 per cent chromium.

FIG. 168.—The induction for a field strength of 10 oersteds of iron-nickel-copper alloys air quenched from 625°C. (1155°F.). (*Von Auwers and Neumann.*[513])

Ellwood and Legg[594] quoted the values for annealed iron-nickel-chromium alloys at low inductions as shown in the table (page 246).

According to results of Nishina,[575] the initial permeability of annealed iron-nickel-chromium alloys can be increased by the addition of tin. An alloy containing 80 per cent nickel and 3 per cent chromium had an initial permeability of 7200; this was increased to 12,800 by the addition of 2.5 per cent tin. Other combinations showed those containing 3 per cent chromium to be more susceptible to tin addition than any others. The 12,800

FIG. 169.—The induction for a field strength of 10 oersteds of iron-nickel-copper alloys annealed at 1100°C. (2010°F.). (*Von Auwers and Neumann.*[513])

value is about what is shown in Table 40 for 3.8 per cent chromium alloys without other addition. Other data are maximum permeability of 40,000, as compared with 62,000 given in Table 40, and a hysteresis loss at 5000 gausses of 25 ergs per cu. cm. per cycle; this may be doubted.

108. Magnetic Properties of Iron-nickel-copper Alloys.—In America the addition of copper to high-permeability alloys of iron and nickel is generally considered less desirable than addition of

FIG. 170.—Section at 40 per cent nickel showing the induction for various field strengths as a function of copper content.   (*Von Auwers and Neumann.*[513])

FIG. 171.—Section at 70 per cent nickel showing the induction for various field strengths as a function of copper content. (*Von Auwers and Neumann.*[513])

chromium or molybdenum because it does not increase electric resistivity so much.   For commercial reasons, copper additions have received considerable attention in Europe, where, according to Campbell,[210] an alloy containing about 75 per cent nickel, 5 per cent copper, and 0.75 per cent manganese, known as "mumetal," first became well known; about 2 per cent chromium is sometimes added.[373]   According to Randall,[464] the material is

Fig. 172.—The initial permeability of iron-nickel-copper alloys air quenched from 625°C. (1155°F.).   (*Von Auwers and Neumann.*[513])

characterized by high initial permeability; its maximum permeability, coercive force, and hysteresis loss are not very different from those of the corresponding iron-nickel alloys.   In Randall's[609] most recent article on mumetal, compositions are not given.   However, the electric resistivity (50 microhm-cm.) quoted is much too high for an iron-nickel-copper alloy of the composition quoted by Campbell.   It may be significant that this is the resistivity of alloys containing about 78 per cent nickel, 2 per cent chromium, and no copper.

The magnetic properties of about 130 iron-nickel-copper alloys were reported by von Auwers and Neumann.[513]   Ring samples were stamped from sheet, then either (1) annealed in dry hydrogen for 1 hr. at 900°C. (1650°F.) and quickly cooled in air from 625°C. (1155°F.), or (2) annealed in dry hydrogen for 2 hr. at 1100°C. (2010°F.) and furnace cooled.   Induction for a field

FIG. 173.—The initial permeability of iron-nickel-copper alloys annealed at 1100°C. (2010°F.).   The broken line represents zero magnetostriction.   (*Von Auwers and Neumann.*[513])

strength of 10 oersteds, as lines of constant induction, is shown in Figs. 168 and 169.   It appeares that induction was less dependent upon heat treatment in the higher copper alloys.   Sections at 40 and 70 per cent nickel (Figs. 170 and 171) show the induction for other field strengths up to 10 oersteds.   The disturbances at about 16 per cent copper in the 70 per cent nickel section and at about 50 per cent copper in the 40 per cent nickel section are associated with low magnetostriction.   Data on initial permeability after the two heat treatments are summarized in Figs.

172 and 173. The peaks of permeability in the ternary space are noteworthy; their location depends upon heat treatment, as may be seen by comparison of the projections of Figs. 172 and 173, or more easily by examination of the projections on a vertical plane of the peaks, given in Fig. 174. For air quenching from 625°C. (1155°F.), the highest initial permeability—more than 13,000—existed in alloys containing a trifle more than 70 per cent nickel and about 12 per cent copper. The annealing treatment shifted the composition of highest initial permeability to lower nickel and higher copper contents.

FIG. 174.—Projection of the peaks of initial permeability of Fig. 173. Numbers indicate nickel contents. (*Von Auwers and Neumann.*[513])

An alloy of iron, nickel, copper, and molybdenum, characterized by very high initial permeability — about 40,000 — was described by Neumann.[504] A composition given as typical was 72 per cent nickel, 14 per cent copper, and 3 per cent molybdenum. Its longitudinal magnetostriction is small ($\Delta l/l = 5 \times 10^{-7}$), which may account for the high value of initial permeability. The maximum permeability of this material is in the neighborhood of 100,000. Coercive force, residual induction, hysteresis loss, and total loss for various inductions are shown in Fig. 175.

109. Properties of Cold-rolled Iron-nickel-copper Alloys.—For some purposes, constancy of permeability over the operating range of inductions is required. Certain hard-rolled alloys, called "isoperms," are used in Germany. Isoperm behavior is illustrated by an idealized hysteresis loop; this is compared with a "normal" loop in Fig. 176.

Among the alloys capable of developing isoperm behavior, those containing iron, nickel, and copper have been investigated extensively in two laboratories, according to Kersten.[495] Most

Fig. 175.—Magnetic properties of an alloy containing about 72 per cent nickel, 14 per cent copper, and 3 per cent molybdenum. Energy losses are for a frequency of 50 cycles. (*Neumann.*[504])

Fig. 176.—A "normal" hysteresis loop (*A*) compared with an "isoperm" loop (*B*). (*Von Auwers and Neumann.*[513])

of the published information, however, has emanated from Dahl and his coworkers. The first report, by Dahl, Pfaffenberger, and Sprung,[445] included data on iron-nickel alloys which are discussed on page 204. In further tests, to determine the most useful combination of stability of permeability (page 206) and hysteresis loss, it was found that copper additions had the desirable effect of shifting the greatest stability to higher degrees of cold work, for which hysteresis loss is lower. Detailed data on the effect of increasing amounts of copper on alloys containing nickel and iron in the 40:60 ratio are given in Table 41. The effect of cooling rate during preliminary heat treatment was found to be important also, as is shown by the data of Table 42.

Several interpretations of isoperm behavior have been offered. Dahl and Pfaffenberger[444] concluded that a special crystal orientation was responsible, because an alloy containing 40 per cent nickel and 15 per cent copper, treated for the best magnetic properties, was "precipitation hardenable" only in so far as magnetic properties and electric resistivity were affected— mechanical hardness underwent no change. In essence they

TABLE 41.—EFFECT OF COLD ROLLING ON MAGNETIC PROPERTIES OF IRON-NICKEL-COPPER ALLOYS PREPARED FROM A 40 PER CENT NICKEL IRON-NICKEL ALLOY*

Copper per cent	Degree of cold reduction, per cent	Initial permeability	Instability, per cent
2.5	25	84.5	1.6
	50	79	0
	70	92	−2.4
	90	100	−7.4
	25	91.5	1.71
	50	91	0.83
	70	110	−0.80
	90	118	−3.41
8	25	91.5	1.20
	50	87	1.20
	70	87.5	1.70
	90	104	1.83
11	25	83	1.70
	50	64.5	1.85
	70	56.5	1.12
	90	63	0.85

* Dahl, Pfaffenberger, and Sprung.[446]

repeated this conclusion a year later[479] by stating that the alloy of greatest value is one "capable of precipitation, but which has to be treated in a way such that . . . it resembles most closely a solid solution that is not precipitation hardenable."

TABLE 42.—EFFECT OF THERMAL TREATMENT OF IRON-NICKEL-COPPER ALLOYS, SUBSEQUENTLY COLD ROLLED 90 PER CENT. THE ALLOYS WERE PREPARED FROM AN IRON-NICKEL ALLOY CONTAINING 36 PER CENT NICKEL*

Copper, per cent	Cooled slowly		Cooled quickly	
	Initial permeability	Instability, per cent	Initial permeability	Instability, per cent
0	91.8	−9.7	97.2	−10.0
3	110.0	−5.6	111.2	−6.6
6	88.5	0.93	105.5	−0.54
8	69.0	0.75	91.0	1 55
10	71.2	−5.56	70.0	0.94
12	55.2	−7.71	44.9	0.46
15	47.2	−7.5	32.9	0.39

* Dahl, Pfaffenberger, and Sprung.[445]

The heat treatment that suppresses precipitation is followed by cold working, and Kersten[495] assumed that such working

FIG. 177.—Directional dependence of magnetic properties of an alloy containing 34.8 per cent nickel and 13 per cent copper, quenched from 1000°C. (1830°F.) then reduced 94 per cent by cold rolling. (*Dahl and Pawlek.*[557])

causes specially oriented precipitation, with respect to the applied pressure, in the individual slip planes. This in turn causes the magnetic anisotropy required for some interpretations of materials exhibiting isoperm behavior which, by the way, is

not restricted to alloys containing nickel, according to Messkin and Margolin.[573]

FIG. 178.—Same as Fig. 177, except that specimens were furnace cooled before cold rolling.   (*Dahl and Pawlek.*[557])

FIG. 179.—The effect of cold rolling on the residual induction and coercive force of an alloy prepared from one containing 40 per cent nickel and 60 per cent iron by the addition of 13 per cent copper.   Preliminary treatment consisted of annealing 2 hr. at 1000°C. (1830°F.).   (*Dahl and Pfaffenberger.*[479])

Cold rolling, as is well known, gives rise to directional dependence of magnetic properties.   This was demonstrated for iron-

nickel-copper alloys by Dahl and Pawlek[557] by results given in Figs. 177 and 178. These diagrams illustrate also two extremes of preliminary heat treatment (on an alloy containing 34.8 per cent nickel and 13 per cent copper). For Fig. 177 the alloy was quenched from 1000°C. (1830°F.) to prevent precipitation, whereas for Fig. 178 the alloy was cooled slowly to permit precipitation. The specimens were then reduced 94 per cent by cold rolling. Quenching resulted in the desired low residual induction and similarity of initial and maximum permeabilities. In fact, the smallness of values of residual induction and maximum permeability as compared with those for the slowly cooled alloy is such that they can hardly be shown on the same scale. The maximum permeabilities are therefore tabulated here:

Angle to rolling direction, degrees	0	30	45	60	90
Maximum permeability	57	92	77	76	81

The latest explanation of isoperm behavior was given by Goldschmidt;[597] it is a brief discussion maintaining that fiber structure is responsible.

110. Other Properties of Cold-rolled Iron-nickel-copper Alloys. Cold rolling has a marked effect on the residual induction and coercive force of iron-nickel-copper alloys. This is shown vividly by Fig. 179, which was constructed from data given by Dahl and Pfaffenberger.[479] Isoperm behavior depends upon the production of a material of low residual induction, and the lowest curve of Fig. 179 shows that residual induction was unusually small for increasing degrees of cold work on the air-cooled (to restrain precipitation) alloy. Hysteresis loops for 90 per cent reduction by cold work for two conditions of heat treatment

FIG. 180.—The effect of preliminary heat treatment on the form of the hysteresis loop of an alloy prepared from a 40 per cent nickel iron-nickel alloy by the addition of 13 per cent copper. Loop I was obtained by slow cooling (which permitted precipitation) before reduction of 90 per cent by cold rolling. Loop II was obtained by rapid cooling before cold rolling. (*Dahl and Pfaffenberger.*[479])

are given in Fig. 180. The optimum copper content for the 40 nickel to 60 iron ratio at 90 per cent reduction lies in the

FIG. 181.—The effect of copper content on the coercive force and residual induction of alloys prepared from a 40 per cent nickel iron-nickel alloy annealed, cooled quickly or slowly, then reduced 90 per cent by cold rolling. (*Dahl and Pfaffenberger.*[479])

FIG 182.—Magnetization curves of alloys containing 45 per cent nickel, with and without 9 per cent copper. Preliminary treatment consisted of annealing 2 hr. at 900°C. (1650°F.) in hydrogen, then 97 per cent reduction by cold rolling. (*Kersten.*[494])

neighborhood of 12 per cent according to the data of Fig. 181.

The effect of annealing 1 hr. on alloys reduced 97 per cent by cold rolling was investigated by Kersten.[494] The alloys were prepared from one containing 45 per cent nickel and 55 per cent iron by the addition of up to 15 per cent copper. Figure 182 shows that without copper the loop was "normal," *i.e.*, residual magnetization was about one-half the saturation value. With 9 per cent copper, however, the ratio of residual to saturation

FIG. 183.—Magnetization curves of a cold-rolled iron-nickel-copper alloy. *I*—without tension. *II*—under a tension of 97,000 lb. per sq. in. (*Kersten.*[494])

magnetization was only 0.06. An unexplained result appeared in the 12 and 15 per cent copper alloys after annealing at 600°C. (1110°F.): residual magnetization was 95 per cent of saturation magnetization. The magnetization curves for this condition were similar to those for the same alloys not heat treated but stressed in tension. An example of the latter is shown in Fig. 183.

111. Hysteresis Loss of Iron-nickel-copper Alloys.—The different character of the hysteresis loops for certain iron-nickel-copper alloys is illustrated by Figs. 180 and 182. In terms of the hysteresis-loop coefficient, there are enough data to infer the trend of variation of hysteresis loss with composition and treatment (in a rather narrow portion of the composition triangle).

FIG. 184.—Hysteresis-loop coefficients of some iron-nickel-copper alloys containing nickel and iron in the 36:64 ratio. (*Computed from data of Dahl, Pfaffenberger, and Sprung.*[445])

FIG. 185.—Hysteresis-loop coefficients of cold-rolled iron-nickel-copper alloys. (*Computed from data of Dahl, Pfaffenberger, and Sprung.*[445])

Such data, obtained by Dahl, Pfaffenberger, and Sprung,[445] are given in Fig. 184 for alloys prepared by the addition of copper to a 36 per cent nickel iron-nickel alloy. Before reduction of 90 per cent by cold rolling, the specimens were annealed, then cooled either quickly or slowly. The curve for the slowly cooled alloys undergoes sharp change of direction between 10 and 12 per cent copper. It is possible that this was caused by precipitation. For rapidly cooled alloys, the change of hysteresis loss with copper content was less marked but similar in nature. The behavior for other degrees of reduction by cold rolling is less clear, as may be seen from Fig. 185, which was plotted also from data of Dahl, Pfaffenberger, and Sprung.[445]

The relative magnitudes of the several core losses, defined on page 234, of alloys treated for constancy of permeability are indicated by the data of Table 43.

TABLE 43.—MAGNETIC PROPERTIES OF IRON-NICKEL-COPPER ALLOYS CONTAINING NICKEL AND IRON IN THE 40:60 RATIO, COLD ROLLED 90 PER CENT TO 0.2 MM. (0.008 IN.)*

Copper, per cent	Initial permeability	Hysteresis-loop coefficient, $a \times 10^6$	Eddy-current coefficient, $e \times 10^9$	Residual-loss term, $c \times 10^6$
11	54	4.6	240	32
13	40	4.4	400	32

* Dahl, Pfaffenberger, and Sprung.[445]

112. Magnetic Properties of Iron-nickel-vanadium Alloys.— Compared with most ternary systems, the iron-nickel-vanadium alloys have been well surveyed, largely by the efforts of Kühlewein,[499] who tested 123 specimens prepared from charcoal iron, shot nickel, and ferrovanadium. (The alloys therefore, according to current standards, were not of high purity.) Ingots were reduced to sheet from which rings were punched, and before magnetic tests all samples were annealed in hydrogen at 900°C. (1650°F.).

The induction of a given iron-nickel alloy may be expected to be decreased by the addition of vanadium, and this expectation is in agreement with the curves of Fig. 186 for 10 per cent vanadium, for field strengths up to 10 oersteds. This section differs from the one for 5 per cent vanadium (not repro-

duced here) in that minima in the vicinity of 80 per
cent nickel appear and the maxima are displaced from
50 to 55 per cent nickel. Further, the highest induction (for a
field strength of 10 oersteds) of the gamma-phase alloys was about

Fig. 186.—The induction for various field strengths of annealed alloys containing
10 per cent vanadium and variable nickel and iron. (*Kühlewein.*[499])

7000 gausses for 10 per cent vanadium, whereas it was about
11,000 for 5 per cent vanadium. Both tendencies are shown
clearly by a projection of lines of equal induction upon the
composition plane. (This diagram is not reproduced.)

Initial permeabilities at 20°C. (68°F.) are shown in Fig. 187.
Of considerable interest is the peak at nearly 80 per cent nickel

Fig. 187.—The initial permeability of annealed iron–nickel–vanadium alloys.
(*Kühlewein.*[499])

and 10 per cent vanadium which represents an initial permea-
bility of over 6000. The peak of maximum permeability
appeared at a somewhat higher nickel content and a lower
vanadium content.

The coercive force for a field strength of 10 oersteds of the iron-nickel-vanadium alloys investigated by Kühlewein was minimum in the neighborhood of 80 per cent nickel, and on the whole was less for 10 per cent vanadium than for 5 per cent vanadium. The last statement was true invariably for residual induction, and both statements were generally true of hysteresis

Additional work on alloys containing 80 per cent nickel and up to 10 per cent vanadium led to the selection of one for experiment containing 7 per cent vanadium. Annealing 1 hr. at 900°C. (1650°F.) resulted in a much flatter curve for permeability versus field strength than that obtained for vanadium-free alloys. It was shown also that the highest initial and maximum permeabilities resulted from an annealing temperature of 1000°C. (1830°F.) and very slow cooling.

However, the permeability characteristics of these alloys are not so suitable as those of alloys containing, for example, molybdenum or chromium. This was noted also by Neumann,[505] and Dahl and Pfaffenberger[479] were evidently of the same opinion, because they abandoned the investigation of vanadium addition after a preliminary test.

113. Properties of Magnetically Soft Iron-nickel-aluminum Alloys.—Magnetic properties of annealed alloys containing 3 and 4 per cent aluminum and nickel and iron in the 40:60 ratio, as given by Dahl and Pfaffenberger,[480] are subjoined:

Aluminum, per cent	Initial permeability	Residual induction, gausses	Coercive force, oersteds	Hysteresis-loop coefficient, $a \times 10^6$
3	1000	3300	0.4	6.3
4	421	2300	0.77	9.1

Increased aluminum content clearly decreases initial permeability and increases hysteresis loss. The influence of cold work on these alloys was reported by Dahl, Pfaffenberger, and Sprung.[445] Figure 188 shows the hysteresis-loop coefficient for low inductions as a function of degree of reduction. The hysteresis loss rises sharply to a maximum during the first stages of cold rolling, then declines to about the original value for 90 per cent reduction.

The initial permeability behaves in reverse order, although the recovery of permeability at 90 per cent reduction is by no means complete, since the permeability fell from 420 to 50 for intermediate reductions, then rose to about 70 for 90 per cent reduc-

Fig. 188.—The effect of cold work on the hysteresis-loop coefficient of an iron-nickel-aluminum alloy containing nickel and iron in the 40:60 ratio and 4 per cent aluminum. (*Computed from data of Dahl, Pfaffenberger, and Sprung.* [445])

Fig. 189.—Hysteresis-loop coefficients as a function of aluminum content for alloys reduced 90 per cent by cold rolling. (*Computed from data of Dahl, Pfaffenberger, and Sprung.* [445])

tion. Hysteresis-loop coefficients as a function of aluminum content for alloys reduced 90 per cent by cold rolling are shown in Fig. 189.

114. Magnetic Properties of Iron-nickel-silicon Alloys.—The effect of the addition of silicon to a 78.5 per cent nickel alloy con-

taining 0.5 per cent manganese was investigated by Nishina.[575] As air quenched from 600°C. (1110°F.) the alloy without silicon addition had an initial permeability of 6500. This was increased to nearly 10,000 by the addition of 1 per cent silicon. In their search for materials having relative constancy of permeability and low hysteresis loss over the operating range of induction, Dahl, Pfaffenberger, and Sprung[445] tried additions of silicon to a 40 per cent nickel alloy but considered their preliminary results

FIG. 190.—The saturation magnetization of iron-nickel-manganese alloys. (*Gumlich, Steinhaus, Kussmann, and Scharnow.*[341])

unsatisfactory. Pfaffenberger[461] determined the effect of reheating on a quenched 71 per cent nickel, 4.8 per cent silicon alloy. The initial permeability underwent a sharp decrease in the 250 to 300°C. (480 to 570°F.) range and was minimum for a reheating temperature of about 725°C. (1335°F.). The coercive force was maximum for the same temperature. After reheating to 725°C. (1335°F.), initial permeability was about 1100, coercive force about 1.3 oersteds, and residual induction about 4000 gausses. Kühlewein[388] measured the time lag of magnetization of 78.5 per cent nickel alloys with and without 1.5 per cent silicon but found nothing ascribable to the presence of silicon.

115. Magnetic Properties of Iron-nickel-manganese Alloys.— Three series of ternary alloys, containing 5, 10, and 15 per cent manganese, were tested by Gumlich, Steinhaus, Kussmann, and Scharnow.[341] The saturation magnetization, as was to be expected, decreased with increased manganese content, and the maximum of magnetization was shifted toward increased nickel to iron ratios, as shown by Fig. 190. The effect of manganese on initial permeability was similar. The reduction of initial permeability by manganese addition was found also by Nishina,[575] who added a maximum of 2 per cent.

Gumlich, Steinhaus, Kussmann, and Scharnow found the effect of cooling rate to become less marked as the manganese content was increased, in agreement with the usual observation for non-ferromagnetic additions; this is illustrated by Figs. 191 to 193.

In practice, these alloys are unimportant magnetically so far; the greatest use of manganese continues to be in the form of small additions to impure alloys to permit satisfactory mechanical working.

FIG. 191.—The initial permeability of iron-nickel-manganese alloys containing 5 per cent manganese. (*Gumlich, Steinhaus, Kussmann, and Scharnow.*[341])

116. Magnetic Properties of Iron-nickel-beryllium Alloys. As is well known, relatively small additions of beryllium to ferrous alloys render them precipitation hardenable. Of the investigators of iron-nickel-beryllium alloys, Kroll[306] tested an alpha-phase alloy containing 5.6 per cent nickel and 1.35 per cent beryllium. Reheating of the quenched alloy increased residual induction from 8.5 to 10 kilogausses, whereas the coercive force of 20 oersteds was unchanged. Preisach[506] added 1 per cent beryllium to a melt containing 55 per cent nickel and 45 per cent

iron; subsequent tests showed that about half of the beryllium was lost during melting and annealing. Magnetic tests after

FIG. 192.—The initial permeability of iron-nickel-manganese alloys containing 10 per cent manganese. (*Gumlich, Steinhaus, Kussmann, and Scharnow.*[341])

FIG. 193.—The initial permeability of iron-nickel-manganese alloys containing 15 per cent manganese. (*Gumlich, Steinhaus, Kussmann, and Scharnow.*[341])

various heat treatments showed that precipitation hardening influenced the coercive force rather more than the initial permeability.

Dahl and Pfaffenberger[479] included beryllium among the metals added to iron-nickel alloys in an attempt to reduce residual induction to abnormally small values in cold-rolled materials, but this addition did not produce the desired effect. All in all, it seems that beryllium is not one of the more useful addition elements.

117. Magnetic Properties of Iron-nickel-silver Alloys.—To determine the effect on the properties of high-permeability iron-nickel alloys of the addition of an element of negligible solubility, Gumlich, Steinhaus, Kussmann, and Scharnow[341] selected silver. Their data, given in Table 44, show that initial permea-

TABLE 44.—MAGNETIC PROPERTIES OF IRON-NICKEL-SILVER ALLOYS*

Composition, per cent		Treatment, cooled from 600°C. (1110°F.)	Initial permeability, μ_0	Coercive force, oersteds
Ni	Ag			
79	...	Rapidly	9000	0.08
75	5	Rapidly	3850	0.23
79	...	Slowly	2000	0.15
75	5	Slowly	2460	0.39
67	...	Rapidly	4800	0.09
67	1.3	Rapidly	2510	0.65
75	...	Rapidly	4500	0.08
71.4	3.6	Rapidly	4170	0.23
75	...	Slowly	2030	0.14
71.4	3.6	Slowly	1990	0.32

* Gumlich, Steinhaus, Kussmann, and Scharnow.[341]

bility was reduced by the addition of silver and that coercive force was increased. Changes in the same direction were found also for slow cooling, as compared with rapid cooling. Information on the effect of aging on the magnetic properties of an iron-nickel alloy containing 2 per cent silver is given in Table 45. Inasmuch as there are no data on solubility relationships of iron-nickel-silver alloys, the meaning of the magnetic-property data is not clear. In addition, they could not be confirmed by Dahl and Pfaffenberger.[479]

TABLE 45.—INFLUENCE OF THERMAL TREATMENT ON AN
IRON-NICKEL-SILVER ALLOY*

Composition, per cent		Treatment	Initial permeability, μ_0	Coercive force, oersteds
Ni	Ag			
77.5	2	Rapidly cooled from 600°C. (1110°F.)	5880	0.16
		Aged 1 hr. at 350°C. (660°F.)	4812	0.20
		Aged 11 hr. at 350°C. (660°F.)	4100	0.32
		Aged 21 hr. at 350°C. (660°F.)	3570	0.37

* Gumlich, Steinhaus, Kussmann, and Scharnow.[341]

B. MAGNETICALLY SOFT ALLOYS OF IRON, NICKEL, AND COBALT

The addition of cobalt to high-permeability iron-nickel alloys produces changes of permeability and hysteresis loss radically different from those produced by the non-ferromagnetic additions. Discovery of this fact was made in 1921, for it was then that Elmen[272] investigated the addition of third elements to gamma-phase alloys of iron and nickel. Measurements on an iron-nickel-cobalt alloy "indicated that up to moderate field strengths the permeability . . . was remarkably constant" in spite of relatively high permeability.

118. Magnetization of Iron-nickel-cobalt Alloys.—The most comprehensive investigation of the magnetic properties of iron-nickel-cobalt alloys was reported by Elmen.[297] The specimens (about 125 compositions in all) were cast from induction-furnace melts of ingot iron, electrolytic nickel, and a "very high grade" of commercial cobalt. These were rolled or swaged to rods, drawn to wire, and flattened to tape. Rings of the tape were packed in a pot, heated to 900 to 1000°C. (1650 to 1830°F.), held at temperature for 1 hr., then furnace cooled to room temperature (in 10 hr.). Such rings were said to be "annealed." Other rings, after annealing, were reheated to 600°C. (1110°F.), then cooled rapidly on a copper plate; these were said to be "air quenched." In some instances a third annealed ring was reheated to 425°C. (795°F.) for 24 hr.; these were said to be "baked." Magnetic properties were reported in the form of perspective diagrams. The first two of these to be considered

are for magnetization of annealed alloys; Fig. 194 is for a field strength of 50 oersteds and Fig. 195 for 1500 oersteds. It is especially clear from Fig. 194 that the greatest magnetization of the series is exhibited by alloys in the vicinity of 50 per cent iron and 50 per cent cobalt. Another interesting part of the diagram

Fig. 194.—Magnetization ($4\pi I$), for a field strength of 50 oersteds, of annealed iron-nickel-cobalt alloys. (*Elmen.*[297])

is the deep valley that originates in the iron-nickel plane at about 30 per cent nickel. Inspection of Fig. 195 shows that the magnetization surface is greatly smoothed by increasing the magnetizing force to 1500 oersteds. The valley in the vicinity of 30 per cent nickel is of much smaller volume.

Other data on the magnetization of iron-nickel-cobalt alloys were given by Masumoto.[308] His results for 1400 oersteds

(when multiplied by 4π since they are given as intensity of magnetization) are in fair agreement with those of Elmen. Judging from Masumoto's magnetization curves for the individual alloys, a field strength in the vicinity of 1500 oersteds is

FIG. 195.—Magnetization ($4\pi I$), for a field strength of 1500 oersteds, of annealed iron-nickel-cobalt alloys. (*Elmen.*[297])

sufficient to magnetize virtually to saturation all iron-nickel-cobalt alloys excepting those of the irreversible group and those containing the hexagonal cobalt structure.

The influence of temperature of measurement on the initial magnetization curves of an alloy containing 45 per cent nickel and 25 per cent cobalt was investigated by Kühlewein.[420]

FIG. 196.—The effect of temperature on the initial magnetization curve of an alloy containing 45 per cent nickel and 25 per cent cobalt.   (*Kühlewein.*[420])

FIG. 197.—The "perminvar" region in the iron-nickel-cobalt composition triangle.   (*Elmen.*[527])

Fig. 198.—Permeability curves for an alloy containing 45 per cent nickel and 25 per cent cobalt. (*Elmen.*[297])

Fig. 199.—Hysteresis loops for maximum inductions of 750, 1000, and 5000 gausses of an alloy containing 45 per cent nickel and 25 per cent cobalt in two conditions of heat treatment (*A*—air quenched, *B*—baked). (*Elmen.*[297])

Results are summarized in Fig. 196.   The influence of structure
on an alloy of the same composition was studied by Dahl and
Pawlek.[523]   The only clear difference resulting from fiber struc-
ture as compared with random structure appeared for specimens
cooled in a transverse magnetic field.   The random-structure

FIG. 200.—The "smooth" form of the hysteresis loop.   The alloy contained
40 per cent nickel and 20 per cent cobalt and was annealed 1 hr. at 1000°C.
(1830°F.).   (*Kühlewein.*[389])

specimen showed the greater magnetization for fields up to 4
oersteds.

119. General Characteristics of Perminvar-type Alloys.—Iron-
nickel-cobalt alloys of composition lying within the ovoid region
indicated in Fig. 197, given by Elmen,[527] are often called "per-
minvars" (invariant permeability).   The characteristic proper-
ties of the group require the aforementioned baking treatment—

heating at about 425°C. (795°F.) for times up to 24 hr.—for their development. The properties so developed may be illustrated by data given by Elmen[297] for an alloy of standard composition; *viz.*, containing 45 per cent nickel and 25 per cent cobalt. Permeabilities as a function of field strength for three conditions of heat treatment are given in Fig. 198. For the baked condition, permeability is shown to be constant for field strengths ranging

Fig. 201.—The "constricted" form of the hysteresis loop. The alloy contained 55 per cent nickel and 35 per cent cobalt and was annealed 1 hr. at 900°C. (1650°F.). (*Kühlewein.*[389])

from 0 to 2.75 oersteds. The initial permeability shown for the annealed condition is greater than for the baked condition, but the range of constant permeability is shorter.

The hysteresis loops for this composition are of interest also. Comparison of the quenched and the baked conditions is made in Fig. 199, in which loops for maximum inductions of 750, 1000, and 5000 gausses are shown. For 750 gausses, the ascending and descending branches coincide for the baked condition, and the loop is degenerated into a single straight line. At 1000 gausses, the loop for the baked condition has measurable area,

but the permeability is nearly constant. The indication of approach to coincidence of the two branches at low values of induction is often realized. This unusual behavior persists at 5000 gausses for the baked condition, for the two branches nearly pass through the origin, forming a "wasp-waisted" loop.

Fig. 202.—The "snakelike" form of the hysteresis loop. The alloy contained 45 per cent nickel and 25 per cent cobalt and was annealed 1 hr. at 900°C. (1650°F.). (*Kühlewein.*[389])

The tendency toward constriction is present in the quenched condition, but is much less marked. Noteworthy also is the fact that the area of the loop for the baked condition is greater than that for the quenched condition at 5000 gausses. This relationship is clearly reversed at lower inductions.

The hysteresis loops characteristic of perminvar-type alloys were studied exhaustively by Kühlewein[389] who classified them as follows:

1. Smooth. This form, illustrated by Fig. 200, is characteristic of alloys containing 40 per cent nickel, 40 per cent iron, and 20 per cent cobalt, annealed at 1000°C. (1830°F.) for 1 hr., and cooled slowly.

2. Constricted. This form, illustrated by Fig. 201, is characteristic of alloys containing 55 per cent nickel, 10 per cent iron, and 35 per cent cobalt, annealed at 900°C. (1650°F.) for 1 hr.

Fig. 203.—The "swollen" form of the hysteresis loop. The alloy contained 25 per cent nickel and 25 per cent cobalt and was annealed 1 hr. at 1000°C. (1830°F.). (*Kühlewein.*[389])

The loop at low inductions is virtually reversible, *i.e.*, virtually without hysteresis.

3. Snakelike. Figure 202 illustrates this type, which is characteristic of alloys containing 45 per cent nickel, 30 per cent iron, and 25 per cent cobalt, annealed at 900°C. (1650°F.) for 1 hr.

4. Swollen. This form, illustrated by Fig. 203, results from annealing at 1000°C. (1830°F.) for 1 hr. alloys of the composition immediately preceding.

5. Tripartite. This form, characterized by Fig. 204, represents the limit in development of perminvar properties. Especially noteworthy is the nearly rectangular portion of the loop. (The composition given is 35 per cent nickel, 20 per cent iron, 45 per cent cobalt; the treatment is annealing at 1000°C. (1830°F.) for 1 hr.) Transition forms exist between the succeeding pairs of types.

Fig. 204.—The "tripartite" form of the hysteresis loop. The alloy contained 35 per cent nickel and 45 per cent cobalt and was annealed 1 hr. at 1000°C. (1830°F.). (*Kühlewein.*[389])

The temperature of annealing has considerable effect on the form of the loop, although the cooling rate is even more important. For example, the form for an alloy containing 65 per cent nickel, 5 per cent iron, and 30 per cent cobalt is of the smooth type after annealing at 900°C. (1650°F.) but nearly of the swollen type after annealing at 1000°C. (1830°F.). Another, that for an alloy containing 35 per cent nickel, 20 per cent iron, and 45 per cent cobalt, is of the swollen type after annealing at 900°C. (1650°F.) but definitely of the tripartite type after annealing at 1000°C. (1830°F.).

120. Initial Permeability of Iron-nickel-cobalt Alloys.—Initial permeabilities of Elmen's[297] annealed alloys, described on page 269, are given in Fig. 205. Since this diagram (and those immediately following) is likely to be of somewhat wider interest than those showing magnetization, it is described in some detail.

FIG. 205.—The initial permeability of annealed iron-nickel-cobalt alloys. (*Elmen.*[297])

Three regions of the diagram are of special interest. The first of these is the iron-nickel plane, or the rear face of Fig. 205. Initial permeability is seen to vary from about 100 to more than 2000 units. Upon addition of nickel to iron, initial permeability declines from about 250 to about 100 at 28 per cent nickel. Further addition of nickel is accompanied by a sharp rise of initial permeability, the maximum (over 2000) being attained at about 45 per cent. Then follow a minimum of about 1200 at

70 per cent nickel, a second maximum of about 1900 at 83 per cent nickel, and finally a rapid decline to about 200 at 100 per cent nickel.

A second region of interest lies in the iron-cobalt plane between 70 and 40 per cent iron, because of the high initial permeability as compared with the surrounding regions.

Fig. 206.—The initial permeability of air-quenched iron-nickel-cobalt alloys. (*Elmen.*[297])

The third region, and the most proper one for description here, lies in the ternary space—and is indicated by the 40 per cent nickel section. It is evident that there exists a maximum of value between 700 and 1000. Alloys in this region are important

because of their substantial constancy of permeability and because of their low hysteresis loss in fields of low strength.

. Sharp changes of initial permeability are effected by air quenching, as may be seen by comparing Fig. 205 with Fig. 206 (and making due allowance for the different scales). Considering first the iron-nickel plane, initial permeabilities are substantially the same for the two conditions of heat treatment up to about 45 per cent nickel. From 45 to 90 per cent nickel, however, large increases are observed. Air quenching increases also the initial permeability of the groups of ternary alloys characterized by virtually constant permeability and low hysteresis loss, although this treatment decreases the constancy of permeability and increases the hysteresis loss.

Further information on the effect of heat treatment was given by Neumann[393]who investigated a series of iron-nickel alloys in the 50:50 ratio, to which 1, 3, 10, 20, and 30 per cent cobalt were added. The 30 per cent cobalt alloy lay within the boundaries of the perminvar region as established by Elmen. Two treatments were applied: (*a*) annealing at 900°C. (1650°F.) for 1 hr. followed by air quenching; (*b*) annealing at 900°C. (1650°F.) for 1 hr., cooling slowly to 625°C. (1155°F.) and holding at this temperature for a short time, followed by air quenching. Any appreciable effect of the difference between the treatments on initial permeability was not discernible. This was equally true of maximum permeability, possibly excepting the 30 per cent cobalt alloy, for which treatment (*a*) yielded somewhat the higher permeability. The effectiveness of treatment (*a*) was proved also for an alloy of standard perminvar composition (50 per cent nickel, 20 per cent iron, and 30 per cent cobalt).

121. Maximum Permeability of Iron-nickel-cobalt Alloys.— Maximum permeabilities determined by Elmen[297] for annealed alloys are shown in Fig. 207. The shape of this surface is similar to that for initial permeability of the same specimens. Elmen gave no diagram for quenched specimens but stated that the permeability surface would also be similar to that for initial permeability. According to a later report by Elmen,[527] maximum permeability in the neighborhood of 200,000 has been obtained in a 45 per cent nickel, 25 per cent cobalt alloy by annealing in hydrogen and cooling in a magnetic field (see also the next section).

122. Effect of Heat Treatment in a Magnetic Field.—That the maximum permeability of iron-nickel-cobalt alloys (as well as that of iron-nickel alloys) can be increased by cooling in a magnetic field was first reported by Kelsall.[492]   Experiments

FIG. 207.—The maximum permeability of annealed iron-nickel-cobalt alloys.
(*Elmen.*[297])

with a 45 per cent nickel, 25 per cent cobalt alloy showed that a field strength of at least 12 oersteds, applied during cooling, brought about the greatest change.   More complete results were given by Dillinger and Bozorth.[515,526]   Ring samples were annealed in purified hydrogen at 1000°C. (1830°F.), then furnace

cooled. They were reheated to a temperature about 50°C. (90°F.) above the magnetic-inversion temperature of the specimen, then cooled in a magnetizing field of 16 oersteds. Magnetic measurements on specimens so treated are given in Table 46 in

FIG. 208.—Hysteresis loops of a tube of alloy containing 45 per cent nickel and 25 per cent cobalt after cooling in a magnetic field. *I*—Loop measured with the field parallel to that applied during cooling. *II*—Loop measured with the field perpendicular to that applied during cooling. (*Dillinger and Bozorth.*[526])

comparison with identical specimens untreated. Other tests showed that the substantial increase of permeability existed only in the direction of the applied field (see page 212). The marked

TABLE 46.—MAGNETIC PROPERTIES OF IRON-NICKEL-COBALT ALLOYS ANNEALED WITH AND WITHOUT A MAGNETIC FIELD*

Composition, per cent			Annealed without magnetic field		Annealed with magnetic field	
Fe	Ni	Co	Maximum permeability	Coercive force, oersteds	Maximum permeability	Coercive force, oersteds
10	70	20	1,490	1.16	11,600	0.28
10	51	39	2,440	2.54	7,100	0.69
11	30	59	1,110	3.86	5,300	2.28
11	11	78	1,730	3.56	4,100	2.54
30	45	25	2,000	0.90	115,000	0.09
30	26	44	1,150	2.90	12,500	0.74
45	45	10	7,550	0.69	18,300	0.44
48	0	52	11,000	0.70	22,400	0.55

* Dillinger and Bozorth.[526]

difference of the parallel and perpendicular directions is shown well by Fig. 208.

FIG. 209.—The effect of composition on the hysteresis loops of materials annealed in a magnetic field (ordinates are inductions in gausses; abscissas are field strengths in oersteds). *A*—60 per cent nickel and 15 per cent cobalt. *B*—10 per cent nickel and 70 per cent cobalt. *C*—65 per cent nickel, no cobalt. *D*—70 per cent nickel and 15 per cent cobalt. (*Dillinger and Bozorth.*[526])

The unusual shape of hysteresis loops of certain iron-nickel-cobalt alloys is noted elsewhere. Dillinger and Bozorth[526] found that heat treatment in a magnetic field sometimes pro-

TABLE 47.—INFLUENCE OF STRUCTURE AND OF TREATMENT ON THE PROPERTIES OF AN ALLOY CONTAINING 45 PER CENT NICKEL AND 25 PER CENT COBALT*

Structure	Annealed	Initial permeability	Maximum permeability	Coercive force, oersteds	Relative residual magnetization
Random..	Without field	600	2,800	0.70	0.1
Random..	In a longitudinal field	5,000	160,000	0.05	0.42
Random..	In a transverse field	450	6,000	0.46	0.30
Fiber.....	Without field	600	2,900	0.90	0.20
Fiber.....	In a longitudinal field	4,000	173,000	0.02	0.20
Fiber.....	In a transverse field	450	1,500	0.62	0.07

* Dahl and Pawlek.[523]

duced pronounced change in the shape of the loops also.   Examples of loops differing from those ordinarily obtained are given in Fig. 209.

The results obtained by Kelsall and by Dillinger and Bozorth were confirmed by Dahl and Pawlek,[523] who, in addition, investigated the effect of fiber structure as compared with random structure.   Data on an alloy containing 45 per cent nickel and

Fɪɢ. 210.- -The hysteresis loss for a maximum induction of 5 kilogausses of annealed iron-nickel-cobalt alloys.   (*Elmen.*[297])

25 per cent cobalt are given in Table 47.   It is to be seen that the highest maximum permeability and the lowest coercive force were obtained in the fiber-structure specimen cooled in a longitudinal field.

123. Effect of Tension on the Permeability of Iron-nickelcobalt Alloys.—The effect of tension on the permeability of an alloy containing 45 per cent nickel and 25 per cent cobalt was reported by Kelsall and Williams[493] by way of illustrating results from a new apparatus for permeability-tension tests.

For an alternating field of 0.01 oersted, permeability was maximum for a tension of 10,000 lb. per sq. in. (for increasing tension). Further increased tension decreased permeability, and recovery was not complete upon release of the load. At 3.5 oersteds, however, permeability attained the maximum value at about 15,000 lb. per sq. in. and underwent no appreciable change up to the greatest load applied—about 30,000 lb. per sq. in. Furthermore, the effect was nearly reversible.

124. Effect of Cold Work on the Permeability of Iron-nickel-cobalt Alloys.—Dahl, Pfaffenberger, and Sprung[445] found an initial permeability of 440 of an alloy containing 45 per cent nickel and 25 per cent cobalt to be reduced to 50 by a reduction of 25 per cent by cold rolling and to 51 by a reduction of 80 per cent.

125. Hysteresis Loss of Iron-nickel-cobalt Alloys.—The best picture of the variation of hysteresis loss with composition of iron-nickel-cobalt alloys is afforded by the data of Elmen[297] given in Fig. 210 for annealed specimens and an induction of 5000 gausses. This surface shows also the abrupt change of values upon passing into the composition region in which only gamma phase exists. Data on a number of alloys for various inductions, also obtained by Elmen,[272] are given in Table 48. The fact that the heat treatment that produces the greatest

TABLE 48.—HYSTERESIS LOSS OF SOME ANNEALED IRON-NICKEL-COBALT ALLOYS*

Composition, per cent		Initial permeability	Maximum permeability	Hysteresis loss and corresponding inductions							
Ni	Co			Gausses	Ergs per cu. cm. per cycle	Gausses	Ergs per cu. cm. per cycle	Gausses	Ergs per cu. cm. per cycle	Gausses	Ergs per cu. cm. per cycle
11.35	68.10	57	1,545	280	8	1,700	1,040	3,950	2,740	15,500	14,160
20.85	49.18	98	1,180	...	..	1,030	299	4,800	3,330	15,200	12,460
20.73	68.35	51	1,447	...	..	.....	.....	5,270	2,605		
45.12	23.83	449	2,075	566	0	1,508	93	5,050	1,185	14,900	3,375
50.47	29.28	231	1,555	560	0	2,000	468	5,000	2,020	13,200	4,965
59.66	14.76	631	2,680	145	0	1,520	88	5,200	632	13,250	1,508
70.29	15.23	390	1,570	320	0	1,470	116	5,000	1,012	10,300	2,435
73.29	5.97	1,430	5,600	500	0	1,530	23	5,100	348	11,500	783

* Elmen.[272]

constancy of permeability in fields of low strength produces also the greatest hysteresis loss in fields of higher strength (described on page 276) is well illustrated by Elmen's data given in Table 49.

TABLE 49.—INFLUENCE OF HEAT TREATMENT ON HYSTERESIS LOSS OF AN ALLOY CONTAINING 45 PER CENT NICKEL AND 25 PER CENT COBALT*

Air Quenched		Annealed		Baked†	
Induction, gausses	Hysteresis loss, ergs per cu. cm. per cycle	Induction, gausses	Hysteresis loss, ergs per cu. cm. per cycle	Induction, gausses	Hysteresis loss, ergs per cu. cm. per cycle
568	18.7	570	0	600	0
722	32	820	9.54	795	0
993	57	974	15.65	1,003	15.27
1,503	119	1,508	93.2	1,604	· 163
5,010	850	5,050	1,185	4,950	1,736
14,810	2,500	14,900	3,375	13,810	4,430

* Elmen.[272]

† At 425°C. (795°F.) for 24 hr.

It was found by Kühlewein[420] that increased temperature of measurement causes a straightening of the sides and approach to square corners of the hysteresis loop, and a decrease of the area of the loop.

126. Residual Induction and Coercive Force of Iron-nickel-cobalt Alloys.—There is little information on residual induction and coercive force as such of iron-nickel-cobalt alloys. Inspection of the hysteresis loops given on preceding pages shows that the values of both may be low or even zero under certain conditions. The variation with temperature of these properties for a 45 per cent nickel, 25 per cent cobalt alloy, as determined by Kühlewein,[420] is shown in Fig. 211.

127. Ferromagnetic Anisotropy of Iron-nickel-cobalt Alloys.— Anisotropy data for eight of the ternary alloys in the nickel corner of the composition triangle were determined by McKeehan[601] by means of magnetization curves taken twice at each of three different temperatures in all instances, and in two instances, of single curves taken at still higher temperature. Data obtained from these curves are collected in Table 50; saturation was attained easily for all alloys. According to McKeehan, the

energy differences $(W_{110} - W_{100})$ and $(W_{111} - W_{100})$ used for computing the anisotropy constants K_1 and K_2 were correct to about $\pm 0.2 \times 10^3$ ergs per cu. cm. The uncertainty of K_1 is thus about $\pm 1 \times 10^3$ and of K_2 not less than $\pm 10 \times 10^3$. The computation of K_0 was made difficult by the variation of the demagnetizing factor N with temperature and by the usual difficulty of evaluating the factor. There is little doubt, according to McKeehan, that the apparent decrease of N with increasing temperature is caused by a real decrease of coercive force.

Fig. 211.—The effect of temperature on the residual induction and coercive force of an alloy containing 45 per cent nickel and 25 per cent cobalt. (Kühlewein.[420])

Graphical representation of the principal constant K_1 as a function of composition (not reproduced here) shows that the best perminvars lie in a region in which anisotropy becomes very small at 400°C. (750°F.) or above. The properties of these alloys are changed considerably by baking at 450°C. (840°F.); consequently, since anisotropy is low, it must be magnetostrictive strains that control largely the directions in which the domains can remain saturated. It appears also from the graphical representation that the sign of K_1 is related simply to the iron or cobalt content of a given alloy, but there are not enough data to be sure. The values of K_2 show no such regularity. Further work is needed before a definite statement can be made.

TABLE 50.—ENERGY DENSITIES AND ANISOTROPY CONSTANTS OF
IRON-NICKEL-COBALT ALLOYS*

Composition, per cent		Temperature		Saturation intensity of magnet-ization	Energy density, ergs per cu. cm. × 10⁻³			Anisotropy constant, ergs per cu. cm. × 10⁻³		
Ni	Co	°C.	°F.		W_{100}	W_{110}	W_{111}	K_0	K_1	K_2
79.3	10.2	22	72	768	10	10 −	8	10	−2	−40
		200	392	710	7	6	5	7	−2	−20
		400	752	560	2	1	1	2	−2	6
		516	961	359	1	1 −	1	1	−3	21
69.4	20.2	22	72	872	23	16	15	23	−29	17
		200	392	822	17	11	11	17	−25	70
		398	748	701	7	4	4	8	−14	29
		598	1108	407	1	1	1	1	0	−6
64.6	14.8	22	72	1005	13	15	12	12	9	−112
		201	394	936	10	10	9	10	−1	−18
		398	748	808	3	2	2	3	−3	2
61.2	28.4	22	72	974	33	24	18	33	−38	−82
		203	397	926	20	16	13	21	−18	−50
		397	747	834	12	10	7	12	−12	−37
60.1	24.8	22	72	1027	23	16	15	23	−26	34
		201	394	971	16	13	11	16	−10	−45
		398	748	857	9	8	7	9	−3	−15
50.8	38.7	22	72	1044	37	20	15	39	−72	−4
		205	401	993	29	17	14	30	−54	41
		398	748	902	15	13	9	15	−9	−102
50.3	24.6	22	72	1152	9	10	11	9	4	16
		205	401	1083	6	7	7	6	4	2
		398	748	973	3	3	3	3	−3	22
40.2	10.2	22	72	1325	13	28	27	13	61	−164
		200	392	1143	8	12	14	8	19	4
		398	748	682	4	5	4	4	7	−59

* McKeehan.[601]

128. Uses of Magnetic Iron-nickel-cobalt Alloys.—According to Elmen,[527] the characteristic properties of perminvar-type alloys render them especially suited to circuits that demand minimum distortion and energy loss. In their disfavor are high cost and necessity of avoiding strong magnetization at any time. A specific suggested use is for loading submarine telephone cables; in this application, the desired high electric resistivity can be obtained by the addition of molybdenum.

129. Other Iron-nickel-cobalt Alloys.—Other elements have been added to iron-nickel-cobalt alloys, but little information is available. This is true of additions of oxygen (in oxide magnets), sulphur, silicon, thallium, zirconium, lead, chromium, and tungsten, for example. A few scattered data may be summarized here, however.

According to Elmen,[527] the following values are typical of an alloy containing 45 per cent nickel, 25 per cent cobalt, and 7 per cent molybdenum: initial permeability, 550; maximum permeability, 3700; saturation magnetization, 10,300 gausses; residual induction, 4300 gausses; coercive force, 0.65 oersted; hysteresis loss for saturation magnetization, 2600 ergs per cu. cm. per cycle; and electric resistivity, 80 microhm-cm.

Gumlich, Steinhaus, Kussmann, and Scharnow[276] determined the effect of heat treatment on initial permeability and coercive force of two alloys containing 50 per cent nickel, 8 per cent manganese, and 2 and 4 per cent cobalt. The largest values of initial permeability—1720 to 2060—and the smallest values of coercive force—0.12 to 0.15 oersted—were obtained by annealing 9 hr. at 1050°C. (1920°F.), then cooling quickly from 930°C. (1705°F.); these may be compared with initial permeability of

TABLE 51.—INFLUENCE OF ANNEALING ON A COLD-DEFORMED ALLOY CONTAINING 70 PER CENT NICKEL, 20 PER CENT IRON, 5 PER CENT COBALT, AND 5 PER CENT MANGANESE*

Electric resistivity, 39 microhm-cm.; coercive force, 2.8 oersteds; initial permeability as cold deformed, 96

Annealed 5 min. at		Electric resistivity, microhm-cm.	Coercive force, oersteds	Permeability, at field strengths of, oersteds,						
°C.	°F.			0†	0.01	0.02	0.03	0.05	0.07	0.10
650	1200	33	1.88	891	892	894	896	899	903	911
675	1245	33	1.03	1940	1950	1962	1980	2015	2060	2140
700	1290	33	0.673	2800	2825	2850	2880	2940	3018	3165
725	1335	33	0.55	2920	2940	2970	2995	3060	3140	3300
750	1380	33	0.46	3010	3040	3070	3110	3190	3280	3470
800	1470	33	0.34	3440	3470	3500	3540	3630	3750	4060

* Gumlich, Steinhaus, Kussmann, and Scharnow.[341]
† Initial permeability.

875 and coercive force of 0.44 oersted obtained without the preliminary high-temperature anneal. Later work by Gumlich, Steinhaus, Kussmann, and Scharnow[341] on an alloy containing 70 per cent nickel, 5 per cent cobalt, and 5 per cent manganese disclosed the possibility of attaining constancy of permeability in weak fields by partial annealing of cold-worked material; experimental data are given in Table 51.

According to Nishina,[575] the addition of 0.3 per cent cobalt to an alloy containing 78.5 per cent nickel, 1 per cent silicon, and 0.5 per cent manganese increased the initial permeability in the air-quenched condition from 9800 to 12,600. Other data given were a maximum permeability of 44,000 and a hysteresis loss of 45 ergs per cu. cm. per cycle.

C. MAGNETIC PROPERTIES OF STRUCTURAL STEELS CONTAINING NICKEL

The magnetic properties of the ordinary structural nickel steels are not very different from those of the corresponding carbon steels. For completeness, however, a few data are summarized here.

130. Magnetic Properties of Iron-nickel-carbon Alloys.— There is little about the magnetic properties of iron-nickel-carbon alloys, or nickel steels, to make them interesting. Of historical interest is the fact that Barrett in 1899, in discussion of Hadfield's[31] well-known paper on "Alloys of Iron and Nickel," reported induction for a field strength of 45 oersteds, residual induction, and coercive force of a series of alloys containing up to 31 per cent nickel and 0.7 per cent carbon.

As is now well known, irreversible nickel steels containing the higher nickel percentages may be obtained in a variety of states, depending on their treatment. This fact was noted by Hilpert and Colver-Glauert[93,94,99,101,102] as a result of measurements made on three steels containing 6 to 31 per cent nickel and 0.24 to 0.37 per cent carbon.

Properties of six nickel steels of familiar engineering grades were determined by Dickie.[295] The specimens contained 0.10 to 0.33 per cent carbon and 2 to 6 per cent nickel and were given various heat treatments. Although the results were reported in detail, it seems sufficient to state that, for a field strength of 150 oersteds, induction ranged from 14 to 19 kilogausses, residual

induction from 8 to 15.5 kilogausses, coercive force from 6 to 14 oersteds, and maximum permeability from 320 to 950.

The effect of heat treatment, *i.e.*, quenching in water or oil from various temperatures, on the saturation magnetization of similar steels was investigated by Maurer and Schroeter;[309] the purpose was to estimate the proportion of retained gamma phase.   The magnetic data, however, are reproduced in Table 52. Only in steel *C* was a significant proportion of gamma phase retained by quenching.

Fig. 212.—The permeability of a nickel-chromium steel containing 0.34 per cent carbon, 4.70 per cent nickel, and 1.54 per cent chromium.   (*Aitchison.*[182])

131. Magnetic Properties of Nickel-chromium Steels.—This group is composed chiefly of irreversible structural steels; their magnetic properties are not of much importance.   Much of the available information has come into existence incidentally, as in investigation of the mechanism of heat treatment.   A good example of this is the contribution of Aitchison,[182] who had no interest whatever in magnetic properties as such, because he was investigating "the low apparent elastic limit of quenched or work-hardened steels."   Permeabilities for three conditions of heat treatment obtained for one steel are given in Fig. 212. Other data on similar steels, obtained by Dickie[251] in an investi-

TABLE 52.—EFFECT OF QUENCHING ON SATURATION MAGNETIZATION OF
SOME NICKEL STEELS*

Quenching temperature		Saturation magnetization, gausses					
		Nickel steel C† quenched in		Nickel steel F‡ quenched in		Nickel-chromium steel G§ quenched in	
°C.	°F.	Water	Oil	Water	Oil	Water	Oil
800	1470	12,620	12,900	20,750	20,060	20,260	19,480
900	1650	5,220	6,190	20,820	20,110	20,340	19,530
1000	1830	6,050	6,280	20,780	20,220	20,330	19,710
1100	2010	5,990	6,220	20,860	20,160	20,330	19,690
1200	2190	7,300	6,770	20,810	20,240	20,330	19,780
Annealed		20,160	20,160	21,200	21,200	20,280	20,280

* Maurer and Schroeter.[209]
† 1.20 per cent carbon, 4.95 per cent nickel.
‡ 0.33 per cent carbon, 3.72 per cent nickel.
§ 0.32 per cent carbon, 2.51 per cent nickel, 1.43 per cent chromium.

TABLE 53.—MAGNETIC PROPERTIES OF SOME NICKEL-CHROMIUM STEELS
FOR A FIELD STRENGTH OF 150 OERSTEDS*

Composition, per cent			Condition†	Induction, gausses	Residual induction, gausses	Maximum permeability	Coercive force, oersteds	Hysteresis loss, ergs per cu. cm. per cycle
C	Ni	Cr						
0.31	4.46	1.41	T	17,500	13,400	368	18.5	102,000
			I	17,200	13,700	484	18.0	90,600
			B	17,200	14,000	505	16.5	89,000
0.31	3.20	0.83	T	18,300	13,400	465	14.7	87,400
			I	18,200	14,700	595	14.7	86,400
			B	18,200	14,800	614	14.0	82,000
0.36	1.90	1.15	T	18,200	13,900	432	16.0	96,000
			I	18,200	15,300	575	14.8	90,500
			B	18,100	15,400	558	15.1	92,600

* Dickie.[251]
† T = tough, I = intermediate, B = brittle; these relative conditions were all produced by suitable heat treatment.

gation of temper brittleness, are given in Table 53; it is to be
seen that variations are of little significance. These may be
taken as characteristic of this type of steel. Data on saturation

induction of the same type of steel, obtained by Houdremont and Schrader, [451] show no perceptible influence of several conditions of heat treatment. All values lay in the immediate neighborhood of 20 kilogausses.

The investigations quoted do not exhaust those which have been reported, but it seems unlikely that a complete review would be justified. In passing, it may be noted that iron-nickel alloys containing substantial amounts of such elements as chromium or molybdenum are non-ferromagnetic and are sometimes useful for this reason.

D. PERMANENT-MAGNET MATERIALS CONTAINING IRON AND NICKEL

The portion of the hysteresis loop that lies in the second quadrant is known as the demagnetization curve. It is shown

FIG. 213.—Schematic diagram showing quantities of importance for permanent-magnet materials.

in terms of induction B and intrinsic induction $B - H$ in Fig. 213. The intersection of the B curve with the $-H$ axis is denoted the $_BH_c$ coercive force; that of the $B - H$ curve is denoted the $_IH_c$ coercive force. The latter can be determined graphically by the intersection of the B curve with the $B = H$ line. The intersec-

tion of the B and the $B - H$ curves with the B axis is known as the residual induction B_r.

If the magnetic circuit contains an air gap, there will be a demagnetizing field (H'_r), consequently the induction is not the residual induction B_r, but is B'_r, determined by the demagnetizing factor N, usually defined by

$$H = H_{app.} - NI = H_{app.} - \frac{N(B - H)}{4\pi}$$

where $H_{app.}$ is the applied field.

If $H_{app.} = 0$, the intrinsic induction is $(B - H)_P$ (at point P), or $B'_r - H'_r$, and

$$H'_r = \frac{N}{4\pi}(B'_r - H'_r)$$

or

$$\frac{N}{4\pi} - \frac{H'_r}{B'_r - H'_r} = \tan \alpha$$

Thus, it is sufficient to know either N or α.

In a magnetic circuit containing an air gap, the B curve is useful for computing the magnetic energy in the gap; this is proportional to the product $B \times H$ and is maximum for definite values of B and H which may be designated B_0 and H_0:

$$B_0 \times H_0 = (BH)_{max.}$$

(This quantity may be converted to ergs per cubic centimeter by dividing by 8π.) The quantity $(BH)_{max.}$, then, is a measure of the maximum magnetic energy in the air gap of a magnet of the most favorable form; in this instance

$$\frac{N}{4} = \tan \alpha = \tan \beta = \frac{H_0}{B_0 - H_0}$$

The quantity $(B_r \times {_B}H_c)$ is often used as a measure of the quality of a permanent-magnet material, but its usefulness is necessarily indirect.

Another useful quantity is the reversible permeability μ_r, defined as the initial slope of a magnetization curve, such as QR, which results from the application of a vanishingly small positive field to a magnet whose state is defined by a point on the demagnetization curve such as Q. Reversible permeability,

ordinarily maximum for a definite value of induction, is a measure of the stability of a permanent magnet toward external—especially alternating—fields: the smaller the reversible permeability, the greater is the stability.

132. Magnetic Properties of Iron-nickel-aluminum Alloys.—The discovery that certain of the iron-nickel-aluminum alloys are useful permanent-magnet materials was announced in the technical press in 1932 by Mishima.[424]   The composition range cited included 10 to 40 per cent nickel and up to 20 per cent

FIG. 214.—Typical properties of iron-nickel-aluminum alloys containing 24 to 28 per cent nickel and 12 to 16 per cent aluminum.   (*Neumann.*[602])

aluminum; a typical composition given was 25 per cent nickel and 12 per cent aluminum.   This alloy was capable of developing a coercive force of about 650 oersteds and a residual induction of about 7500 gausses.   Typical properties given by Neumann[602] are shown in Fig. 214.   Added advantages were found to be increased resistance to the demagnetizing influences of increased temperature and mechanical shock.

Mishima's discovery was followed by further investigation, notably by Köster,[456] Zaimovsky, Naroditzky, and Loubovitch,[511] Messkin and Somin,[501] and Pölzguter.[538]   Köster seems to have been first to recognize the part played by precipitation hardening.   Permanent magnetism is now believed to be somehow connected with intense internal strain of the kind that is produced at a certain stage of precipitation.   Required, of

course, is an alloy having a large temperature coefficient of solubility. Examples of increased coercive force and residual induction as given by Köster are reproduced in Fig. 215. In other specimens, coercive force as high as 600 oersteds was obtained, in agreement with Mishima's finding.

Messkin and Somin[501] obtained the degree of precipitation and particle size corresponding to the most useful values of the

FIG. 215.—The effect of tempering on the magnetic properties of iron-nickel-aluminum alloys quenched from 1200°C. (2190°F.). (*Köster.*[456])

magnetic properties by adjusting the cooling rate to suit alloy composition; the adjustment was effected by varying the section size. Experiments with nine alloys showed, among other things, that a field strength of 4000 oersteds was sufficient to magnetize them to practical saturation. For alloys containing about 25 per cent nickel and 12 to 18 per cent aluminum, the greatest coercive force existed in increasingly large sections as the nickel content was increased. The data assembled in Table 54 show that quenching followed by reheating is essential if the highest

residual induction is required, although indication was found that subsequent heat treatment cannot increase the values of residual induction and coercive force resulting from the optimum cooling rate of the casting.

The conclusion of Messkin and Somin that optimum section size increases with increased aluminum content in 25 per cent nickel alloys was confirmed by Pölzguter;[538] specifically, increasing aluminum content from 12.7 to 15.2 per cent increased the optimum section thickness from 5 to 25 mm. (0.197 to 0.984 in.). It was found also that the $(BH)_{max.}$ energy product could be increased by heating the castings to 1200°C. (2190°F.) then cooling slowly to 650°C. (1200°F.); furthermore, this treatment tended to eradicate differences ascribable to differences of section size. Alloys of higher nickel content (9 to 14 per cent) required rapid cooling for development of the most desirable combination of values of residual induction and coercive force. This required either casting into metal molds or quenching after reheating to 1150 to 1250°C. (2100 to 2280°F.). Furthermore, reheating for 30 min. to 3 hr. at 670°C. (1240°F.) was found to be desirable.

TABLE 54.—EFFECT OF HEAT TREATMENT ON MAGNETIC PROPERTIES OF SOME IRON-NICKEL-ALUMINUM ALLOYS*

Composition, per cent		Specimen thickness	Sand cast		Water quenched from 1100°C. (2010°F.)		Air cooled from 1100°C. (2010°F.)		Reheated 1 hr. at 700°C. (1290°F.)		Water quenched from 1100°C. and reheated at 700°C.	
Ni	Al	in.	B_r†	H_c‡	B_r	H_c	B_r	H_c	B_r	H_c	B_r	H_c
25.50	12.40	18.0 / 0.709	3700	330	6100	165	4100	430			7000	316
		5.5 / 0.217	5800	490	1400	10	5300	500			6750	295
23.25	13.75	18.5 / 0.728	4900	415	3900	25	6000	475	5400	375	7950	255
		3.5 / 0.138	6400	105					6800	225	7850	255
25.96	17.62	19.0 / 0.748	4600	500	1200	4.5	5400	430	5000	430	6400	345
		5.7 / 0.224	5800	60					6100	290	6350	315

* Messkin and Somin.[501]
† Residual induction, gausses.
‡ Coercive force, oersteds.

There is evidence that the state of highest coercive force in iron-nickel-aluminum alloys is one in which actual precipitation of a second phase has not yet occurred. This was the conclusion of Glocker, Pfister, and Wiest,[485] who measured the lattice constant and diffraction-line width of an alloy heated for various periods at 720°C. (1330°F.); for the state of maximum coercive force, there was change of neither lattice constant nor line width. This agrees with the opinion of Burgers and Snoek[516] that, for maximum coercive force, precipitation "has reached only a very preliminary stage, resulting in the formation of a highly stressed state in the lattice. .·. . " Precipitation does occur after continued heating, however; this was shown by Ellis and Schumacher[482] among others.

It has been shown that the highest coercive force of the alloy corresponding in composition to Fe_2NiAl results from cooling at a definite rate. This results, according to Bradley and Taylor,[589]. in small "islands" of iron-rich alpha phase on the verge of being precipitated. Because of difference between the lattice constants of these clusters and those of the actual precipitate toward which they tend, a condition of intense strain exists which is conducive to high coercive force.

133. Magnetic Properties of Iron-nickel-cobalt-aluminum Alloys.—Recent years have brought about drastic changes in permanent-magnet materials. Most of the information on these materials of unprecedented magnetic energy lies buried in patent literature, but enough exists in sources open to this review to permit brief description. From the standpoint of the user, Fink's[562] article can be recommended: it seems that the extraordinary permanence and energy of the new materials open a field which was closed to the well-known tungsten, chromium, and cobalt steels, *viz.*, radio loud-speaker parts, among others.

The essential point about the new magnet alloys is that they are precipitation hardening, and aluminum is one element that produces the desired effect in iron-nickel alloys and in iron-nickel-cobalt alloys. The alloys must, of course, be heat treated for best results. (In this connection, the X-ray investigation of Glocker, Pfister, and Wiest[485] may be cited.) They usually can be neither hot worked nor machined, hence the castings must be finished by grinding.

A typical composition for the iron-nickel-cobalt-aluminum type is 20 per cent nickel, 5 per cent cobalt, and 12 per cent aluminum. According to Fink,[562] a field strength of 2000 oersteds is required to produce practical saturation. The coercive force and residual induction of the material are resistant to temperature, mechanical shock, and alternating fields to an extent unknown in the older alloys. Data on magnetic properties, reported by Pölzguter,[538] Mishima (as quoted by von Auwers[552]), and MacMillan,[571] are assembled in Table 55.

TABLE 55.—MAGNETIC PROPERTIES OF SOME
IRON-NICKEL-COBALT-ALUMINUM ALLOYS

Reference	Composition, per cent			Residual induction, gausses	Coercive force, oersteds	$B_r \times H_c$	Energy product, $(BH)_{max.}$
	Ni	Co	Al				
MacMillan[571]........	20	5	12	7,750	460	3,570,000	1,630,000
	28.2	5.4	9	5,050	725	3,660,000	1,200,000
Pölzguter[538].........	24.5 to	5 to	9 to	6,000 to	750 to	5,160,000*	1,650,000*
	30	10	13	6,500	900		
Mishima, quoted by von Auwers[552].........	17	5	9	9,400	160	1,500,000	
	16	10	9	10,000	185	1,850,000	
	24.8	5	10.2	9,800	290	2,850,000	
	12	4.5	29.5	9,600	510	4,900,000	
	12.4	30	7	9,500	180	1,600,000	

* Mean value.

Typical data for alloys containing 24 to 30 per cent nickel, 9 to 13 per cent aluminum, and 10 per cent cobalt, given by Neumann,[602] are shown in Fig. 216. The values of the energy products are seen to be high as compared with, for example, those for the standard 3 per cent chromium or 5 per cent tungsten steels, for which a representative value is 350,000 gauss-oersteds.

In time, it is likely that more thorough details will become available in the technical literature, consequently the brief description given here will probably be adequate for most purposes.

134. Magnetic Properties of Iron-nickel-cobalt-titanium Alloys.—Another of the recently discovered permanent-magnet materials, containing 10 to 25 per cent nickel, 15 to 36 per cent cobalt, and 8 to 25 per cent titanium, was described by Honda,

Masumoto, and Shirakawa.[490]   Typical properties given by Neumann[602] are shown in Fig. 217.   This type of alloy is also precipitation hardening, and its discoverers stated that the best

FIG. 216.—Typical properties of iron-nickel-cobalt-aluminum alloys containing 24 to 30 per cent nickel, 9 to 13 per cent aluminum, and 5 to 10 per cent cobalt.   (*Neumann.*[602])

FIG. 217.—Typical properties of iron-nickel-cobalt-titanium alloys containing 10 to 25 per cent nickel, 15 to 30 per cent cobalt, and 8 to 25 per cent titanium. (*Neumann.*[602])

properties are developed by heating the castings to 660°C. (1220°F.).   After magnetizing in a field of 10,000 oersteds, the residual induction ranged from 6300 to 7600 gausses, and coercive

force ranged from 780 to 920 oersteds.   The resistance to heat and vibration described in the preceding section was found in these alloys, and the energy products are the greatest of any yet reported for ferrous materials.

The most spectacular permanent-magnet material reported to date contains no iron.   Jellinghaus[555] found an energy product of nearly 4,000,000 (coercive force about 2700, residual induction

Fig. 218.—The coercive force of iron-nickel-copper alloys air quenched from 625°C. (1155°F.).   (*Von Auwers and Neumann.*[513])

about 4500) for an alloy containing 76.7 per cent platinum and 23.3 per cent cobalt quenched from 1200°C. (2190°F.).

135. Magnetic Properties of Iron-nickel-copper Alloys.—The coercive force of iron-nickel-copper (and other) alloys undergoes little change with changed composition provided that the alloys remain homogeneous.   This is indicated by the data of Kussmann and Scharnow[307] given in Table 56.   A substantial increase occurs, however, when a second phase appears; this is ascribed[307] to stresses induced by the different coefficients of

TABLE 56.—COERCIVE FORCE OF SOME IRON-NICKEL-COPPER ALLOYS
PREPARED FROM A 50 PER CENT NICKEL IRON-NICKEL ALLOY*

Composition, per cent		Number of phases present	Coercive force, oersteds
Ni	Cu		
50	0	1	0.21
47.7	4.6	1	0.24
46.3	7.4	1	0.24
45	10.0	1	0.23
43.8	12.6	1	0.28
42.5	15.0	1	0.27
41.3	19.4	2	3.0
37.2	25.6	2	10.7
34.8	30.6	2	13.9
30.2	39.6	2	21.0
25.0	50.0	2	24.4

* Kussmann and Scharnow.[307]

TABLE 57.—RESIDUAL INDUCTION AND COERCIVE FORCE OF
IRON-NICKEL-COPPER ALLOYS*

Composition, per cent		Residual induction, gausses	Coercive force, oersteds	$B_r \times H_c$†
Ni	Cu			
37	55	1,650	90	149,000
36	54	2,050	215	440,000
35	52.5	2,500	215	538,000
34	51	2,950	215	635,000
32	48	3,500	185	645,000
30	45	3,800	87	330,000
20	30	4,000	20	80,000
40	50	2,200	105	231,000
40	45	3,450	172	593,000
40	40	4,800	155	745,000
40	30	6,800	80	340,000
30	60	1,950	315	600,000
30	55	2,800	240	672,000
25	65	1,430	410	586,000
25	60	2,300	210	483,000
25	55	2,850	135	398,000

* Dahl, Pfaffenberger, and Schwartz.[525]
† This product is not directly comparable with the $(BH)_{max}$. product, values for which were
not given.

thermal expansion of the phases. The increase was carried
to its extreme by Dahl, Pfaffenberger, and Schwartz,[525] who
subjected alloys to precipitation treatment with the results
shown in Table 57; these may be compared with those of
von Auwers and Neumann[513] given in Figs. 218 and 219. It
seems that the coercive force of some of the alloys can be changed
a thousandfold by heat treatment.

FIG. 219.—The coercive force of iron-nickel-copper alloys annealed at 1100°C.
(2010°F.). (*Von Auwers and Neumann.*[513])

The work of Dahl, Pfaffenberger, and Schwartz was confirmed
by Neumann[536] who obtained even higher values for coercive
force and $B_r \times H_c$. For example, an alloy containing 20 per
cent nickel and 62 per cent copper, cast, then heated 2 hr. at
600°C. (1110°F.), had a coercive force of 445 oersteds and a
residual induction of 3020 gausses.

It is an interesting fact that these alloys undergo no con-
siderable change of mechanical hardness during the treatment
that produces the greatest coercive force. Furthermore, the

material can be worked mechanically; in fact, the subjoined data of Dahl, Pfaffenberger, and Schwartz,[525] for an alloy containing 40 per cent nickel and 40 per cent copper, indicate that from the

Fig. 220.—The effect of rolling direction on the magnetic properties ($_IH_c$, B_r, $(BH)_{max}$, μ_0, and μ_{max}.) of an iron-nickel-copper alloy containing 20 per cent nickel and 60 per cent copper. (*Neumann, Büchner, and Reinboth.*[503])

standpoint of permanent-magnet materials an even better combination of properties results from mechanical working:

Treatment	Residual induction, gausses	Coercive force, oersteds	$B_r \times H_c$
Cooled slowly from 1050°C. (1920°F.).....	4800	155	745,000
Same; then stretched 30 per cent.........	5600	177	992,000

Iron-nickel-copper alloys for permanent magnets were investigated in considerable detail recently by Neumann, Büchner, and

Reinboth.[603]   It was found that those most useful contained in
the neighborhood of 60 per cent copper, 20 per cent nickel, and
20 per cent iron.   Such materials can be forged and cold worked
without difficulty.   The magnetic properties of the cast alloys
were improved by a heat treatment consisting of air quenching
from about 1000°C. (1830°F.) followed by reheating to about
600°C. (1110°F.).   The highest values obtained in this way were
residual induction, 3420 gausses; coercive force, 390 oersteds;
and $(BH)_{max.}$, 533,000 gauss-oersteds.   Further improvement
resulted from severe cold rolling followed by annealing.   The

FIG. 221.—Demagnetization curves of rolled and heat-treated iron-nickel-copper
alloys containing 20 per cent nickel.   (*Neumann, Büchner, and Reinboth.*[603])

highest values obtained were residual induction, 6000 gausses;
coercive force, 490 oersteds; and $(BH)_{max.}$, 1,460,000 gauss-oersteds.
Such treatment results in strong directional dependence of the
magnetic properties, as is shown by Fig. 220.

Demagnetization curves for cold-rolled and heat-treated alloys
containing 20 per cent nickel are given in Fig. 221.   It is to be
seen that the magnetic properties of these alloys are about those
of the high-alloy cobalt-chromium steels.   The effect of varying
degrees of cold reduction on the properties of the 20 per cent
nickel, 60 per cent copper alloy is shown in Fig. 222.

Another group of iron-nickel-copper alloys used as permanent-
magnet materials contains much less copper than those investi-

gated by Neumann, Büchner, and Reinboth. According to Legat,[600] the magnetic hardness of these alloys results from precipitation· of a copper-rich phase and from gamma-alpha transformation. The favored composition seems to be 15 per cent nickel and 14 to 15 per cent copper; in an alloy heat treated for greatest hardness, the coercive force is about 300 oersteds and the residual induction is about 1500 gausses. Tests with other addition elements led to the conclusion that they result in no improvement. These alloys also have the advantage of being

Fig. 222.—Demagnetization curves of an iron-nickel-copper alloy containing 20 per cent nickel and 60 per cent copper; *a*—wire reduced 96 per cent to 0.3 mm.; *b*—wire reduced 89 per cent to 0.5 mm.; *c*—sheet reduced 50 per cent to 0.05 mm. (*Neumann, Büchner, and Reinboth.*[603])

mechanically workable, although their energy products are not so great as those of other iron-nickel-copper alloys.

E. AUTHOR'S SUMMARY

1. There are three classes of effects of addition elements on the magnetic properties of iron-nickel alloys. First, such elements as chromium, copper, molybdenum, silicon, and vanadium reduce the sensitivity of the alloys to heat treatment and thus facilitate the development of high permeability without rigorous control of cooling rate. Furthermore, the initial permeability and electric resistivity are ordinarily increased. Second, the addition of the ferromagnetic element cobalt causes radical modification of the permeability and hysteresis characteristics of the

high-permeability materials.   Third, additions of such elements as aluminum and titanium cause great magnetic hardness.

2. In America the most important non-magnetic additions to soft alloys are molybdenum and chromium.   These elements, to a maximum of 3.8 per cent, increase initial permeability and electric resistivity.

3. In Europe there has been considerable discussion of the effect of copper additions on alloys in both the soft and the hard-rolled conditions.   In small amounts copper is not harmful magnetically, but the increase of electric resistivity is much less than that caused by chromium or molybdenum.   In larger amounts, for which there is substantial decrease of saturation magnetization, copper may cause relatively high initial permeability.   For example, an initial permeability of over 13,000 has been reported for an air-quenched alloy containing about 70 per cent nickel and 12 per cent copper.   The highest initial permeability ever reported (about 40,000) was for an alloy containing 72 per cent nickel, 14 per cent copper, and 3 per cent molybdenum.   Further additions of these elements produce magnetically hard materials.

Special treatment consisting mostly of drastic cold rolling results in special magnetic behavior, such as constancy of permeability over a range of inductions.   Of the materials tested, results on iron-nickel-copper alloys have been reported most extensively.

4. Additions of aluminum, manganese, silicon, and vanadium have been investigated, but they are less useful than molybdenum or chromium.

5. Magnetically soft alloys of iron, nickel, and cobalt exhibit, under certain conditions, great constancy of permeability over a range of inductions and are characterized by hysteresis loops of special shapes.   Their variation with composition and heat treatment is illustrated by Figs. 200 to 204.   These properties have led to very useful applications.

6. The magnetic properties of the ordinary structural nickel steels are not very different from those of the corresponding carbon steels.

7. In recent years magnetically hard alloys containing iron and nickel have become important permanent-magnet materials. The alloys fall into distinct groups, *viz.*, iron-nickel-aluminum,

iron-nickel-cobalt-aluminum, iron-nickel-cobalt-titanium, and iron-nickel-copper alloys. The quaternary alloys have the greatest energy and permanence known in ferrous materials, but in common with the iron-nickel-aluminum alloys, they cannot be worked mechanically and castings must be finished by grinding. The iron-nickel-copper alloys, however, can be worked mechanically.

MECHANOMAGNETIC PROPERTIES

Magnetostriction of Iron-nickel Alloys—Magnetostriction of Complex Alloys. Other Effects—Author's Summary

Magnetization of ferromagnetic substances is accompanied by mechanical effects such as change of length. Of these effects, two are fundamental; others are either special cases or combinations. The first fundamental effect is the Joule effect, or the change of length in the direction of the magnetic field. The second is the Villari effect, or the change of magnetization caused by the application of longitudinal stress. The Joule effect is well known as longitudinal magnetostriction. Similarly, the transverse Joule effect, or the change of length normal to the direction of the magnetic field, is known as transverse magnetostriction.

The change of volume—volume magnetostriction—accompanying magnetization is the Barrett effect. Its inverse, the change of magnetization caused by pressure, is the Nagaoka and Honda effect. The Wertheim effect and its inverse effect relate bending and magnetization; the Wiedemann effects relate twisting and circular magnetization.

The mechanomagnetic effects are of little technologic importance. Of the existing information, most is on magnetostriction. One use of this effect, suggested by Pierce,[285] was as an oscillator to control high-frequency circuits; on the whole, investigators have been seeking clews to the nature of ferromagnetism rather than practical applications. However, useful results have been forthcoming from such studies even though they have not shed much light on ferromagnetism, *e.g.*, knowledge of the effect helped in the formulation of a plausible explanation of the high permeability of permalloy, as by McKeehan.[238]

A. MAGNETOSTRICTION OF IRON-NICKEL ALLOYS

The phenomenon of magnetostriction—or change of dimensions of a ferromagnetic body upon magnetization—has been

known nearly a hundred years. Its initial description is generally credited to Joule, hence the term "Joule effect." In this connection Joule's[5] own words are of interest:

About the close of the year 1841, Mr. F. D. Arstall, an ingenious machinist of this town, suggested to me a new form of electro-magnetic engine. He was of the opinion that a bar of iron experienced an increase of bulk by receiving the magnetic condition; and that, by reversing its polarity rapidly by means of alternating currents of electricity, an available and useful motive power might be realized. At Mr. Arstall's request I undertook some experiments in order to decide how far his opinions were well-founded.*

In brief, Joule found elongation of iron and steel in the direction of the axis of magnetization and contraction in the transverse direction. It remained for Barrett[7] to discover, on Sept. 9, 1873, that nickel contracts in the direction of the axis of magnetization, but it was not until the turn of the century, when the Japanese school became active, that systematic study of magnetostriction was begun.

136. Early Data on Iron-nickel Alloys.—The first measurement of magnetostriction of iron-nickel alloys was probably made by Nagaoka and Honda[43] and reported in 1902. Specimens, of French origin, were in the form of slender ovoids, or of wires, and contained about 0.3 per cent carbon and respectively 25, 29, 36, and 46 per cent nickel. All were found to elongate in the direction of the magnetic field. The degree of elongation was greater for any one alloy in the annealed condition than in the hard-drawn condition. The volume change (increase) upon magnetization was found to be nearly proportional to the field strength and of unusually large magnitude. These investigators reported further results on alloys containing from 25 to 70 per cent nickel in the following year.[53] Their data are summarized in Figs. 223 to 226. It is noteworthy that the change of volume upon magnetization is ordinarily small compared with the change of length (the volume change is a combination of longitudinal expansion and lateral contraction); the large increase of volume in the vicinity of 30 per cent nickel forced Nagaoka and Honda to the conclusion that such alloys expand in both directions. This was verified later by direct measurement.

* For a more complete history of magnetostriction, see McKeehan's[237] review.

Measurements on the same series of alloys were extended to liquid-air temperature by Honda and Shimizu.[63] Elongation in the direction parallel to the magnetic field of moderate and high strengths was invariably greater at liquid-air temperature

FIG. 223.—Variation of magnetostriction with field strength. (*Nagaoka and Honda.*[53])

FIG. 224.—Variation of magnetostriction with composition for field strengths of 400 oersteds. (*Nagaoka and Honda.*[53])

than at ordinary temperature.   Alloys in the 20 to 30 per cent nickel range underwent large changes during refrigeration; it is now known, of course, that these were the result of gamma-alpha transformation.

FIG. 225.—Variation of volume magnetostriction with field strength. (*Nagaoka and Honda.*[53])

FIG. 226.—Variation of volume magnetostriction with composition (*Nagaoka and Honda.*[53])

Fifteen years elapsed before further data appeared. Honda and Kido,[151] in order to fill in the gaps in the earlier work, investigated 10 specimens. The alloys cannot have been very pure, because the iron contained nearly 0.1 per cent carbon and

FIG. 227.—Magnetostriction of iron-nickel alloys at 9°C.   (*Honda and Kido.*[151])

FIG. 228.—Variation of magnetostriction with concentration.   (*From data of Honda and Kido.*[151])

the usual amounts of other impurities found in mild steel. The nickel contained about 0.3 per cent carbon, 4.2 per cent copper, and smaller amounts of other impurities. Results of magnetostriction measurements are summarized in Fig. 227; they agree,

in general, with the earlier data of Nagaoka and Honda, when comparable. These curves permit construction of other curves showing the variation of magnetostriction with concentration for various field strengths. This has been done in Fig. 228. Two maxima are evident, and the change of sign occurs at approximately 77 per cent nickel.

Fig. 229.—Variation of magnetostriction with magnetization. (*McKeehan and Cioffi.*[239])

The work of Honda and Kido was repeated by Masumoto and Nara,[264] who used alloys of somewhat higher purity. Results were qualitatively similar; the change of sign, however, was found to be at 81 per cent nickel.

137. Later Data.—Magnetostriction of wires in weak fields was measured by McKeehan and Cioffi.[239] Specimens included

iron, nickel, and seven alloys ranging from 45.57 to 89.43 per cent nickel. The method permitted simultaneous measurement of

FIG. 230.—Variation of magnetostriction with field strength. (*McKeehan and Cioffi.*[239])

FIG. 231.—Variation of saturation magnetostriction with composition. (*McKeehan and Cioffi.*[239])

magnetostriction and magnetization in a uniform field of strength up to 40 oersteds. Results are summarized in Fig. 229, which

shows magnetostriction $\Delta l/l$ plotted against magnetization $B - H$. The upper limit of field strength of 40 oersteds was sufficient to saturate the alloys, but not iron or nickel. It is to be observed that the initial slope of all magnetostriction-magnetization curves is zero; this fact is verified by the representative data of Table 58. Further, as magnetization approaches saturation value, magnetostriction approaches a limiting value. Magnetostriction as a function of field strength is shown for several specimens in Fig. 230. The variation of saturation magnetostriction with composition is shown in Fig. 231.

TABLE 58.—MAGNETOSTRICTION IN WEAK FIELDS*

Nickel, per cent	Field strength, H, oersteds	Magnetization, $B - H$, gausses	Magnetostriction, $\Delta l/l \times 10^9$
100	0.044	11	0
	0.089	22	0
	0.177	58	−3
	0.263	114	−7
	0.349	214	−41
	0.513	603	−230
	†	†	†
	31.3	5,630	−31,620
80	0.016	39	0
	0.047	163	0
	0.085	564	0
	0.121	1,440	0
	0.210	3,690	0
	0.447	6,720	+7
	†	†	†
	40.0	10,400	+1,150
0	0.441	184	0
	†	†	†
	8.95	14,920	426
	12.54	15,300	440
	17.00	15,720	460
	22.0	15,940	452
	27.6	16,320	451
	32.6	16,580	436
	39.4	16,650	420

* McKeehan and Cioffi.[239]
† Indicates omission of intermediate values.

A comprehensive series of measurements of magnetostriction of iron, nickel, and iron-nickel alloys was made by Schulze.[236] It was found, in agreement with results of other investigators, that iron at ordinary temperature first expands, then, at higher field strengths, contracts. The change of sign shifts to lower field strength as purity increases.

Contraction was found invariably for several grades of nickel, as is shown by the data of Table 59. It is to be noted that, for any given field strength, the contraction increases with increasing purity.

TABLE 59.—MAGNETOSTRICTION OF THREE GRADES OF NICKEL*

Field strength, oersteds	Magnetostriction, $\Delta l/l \times 10^6$		
	99.2 per cent nickel†	0.01 per cent carbon electro-lytic nickel‡	0.1 per cent carbon electro-lytic nickel‡
5.6	−3.83	−4.37	
8.4	−5.51		
11.2	−6.70	−7.84	−4.90
16.9	−9.58		
22.5	−11.68	−13.80	−10.86
33.8	−14.56	−16.89	−14.86
45.1	−16.87	−19.08	−17.19
56.4	−18.59	. . . . . .	−18.70
67.6	−19.79	−21.34	−20.06
78.9	−20.77		
90.2	−21.60	−22.93	−21.95
101.5	−22.21		
112.8	−22.83	−23.91	−23.38
141.0	−23.69	−24.81	−24.06
169.2	−24.35	−25.34	−24.74
225.6	−25.09	−26.01	−25.87
282.0	−25.62	−26.40	−26.17
338.4	. . . . . .	. . . . . .	−26.39

* Schulze.[236]
† 0.7 per cent manganese.
‡ 0.81 per cent cobalt.

The first series of alloys measured by Schulze contained 0.4 to 1.7 per cent manganese and 0.01 to 0.03 per cent carbon. The magnetostriction data are summarized in Fig. 232, which shows the variation of length change with field strength. Variation of

magnetostriction with nickel content for various field strengths, obtained from the curves of Fig. 232, is given in Table 60 and

FIG. 232.—Magnetostriction of iron-nickel alloys; variation of length change with field strength. (*Schulze.*[286])

FIG. 233.—Magnetostriction for various field strengths of iron-nickel alloys; variation of magnetostriction with nickel content. (*Schulze.*[286])

Fig. 233. The existence of two maxima, as found by Honda and Kido, is to be noted; the zero point at 30 per cent nickel is a consequence of the fact that that alloy was non-ferromagnetic.

Magnetostriction of the gamma-phase alloys, *i.e.*, those containing more than about 30 per cent nickel, changes sign between 80 and 81 per cent nickel, being positive for lower nickel contents and negative for higher nickel contents. This is in agreement with the finding of Honda and Kido.

TABLE 60.—SUMMARY OF MAGNETOSTRICTION OF IRON-NICKEL ALLOYS*

| Nickel, per cent† | Magnetostriction, $\Delta l/l \times 10^6$ | | | | | |
| | Field strength, oersteds | | | | | |
	5	10	25	50	150	250
0	0.30	2.05	4.63	6.12	4.38	−1.28
3.1	0.50	2.15	9.20	12.81	13.53	13.53
11.4	0.32	0.78	2.54	7.89	19.30	24.98
21.0	0.15	0.40	1.47	5.11	20.78	28.62
29.7	0	0	0	0	0	0
31.3	0.30	0.93	1.97	2.76	3.91	4.36
(36)‡	(1.50)	(3.10)	(10.00)	(17.60)	(21.75)	(21.98)
41.5	0.77	2.25	12.50	20.03	25.46	26.70
50.6	1.16	4.30	15.87	22.57	26.10	26.40
61.1	2.63	5.75	15.72	19.25	22.90	23.67
69.5	2.20	5.95	11.85	13.96	15.86	16.00
77.0	1.15	2.82	5.48	5.82	6.00	6.00
79.4	0.38	1.25	2.51	2.72	2.72	2.72
82.5	−0.46	−2.95	−3.13	−3.13	−3.13	−3.13
89.5	−1.20	−5.26	−11.71	−12.63	−12.66	−12.66
99.2	−3.50	−6.07	−12.38	−17.62	−23.98	−25.38

* Schulze.[286]

† Maximum carbon, 0.03 per cent; maximum manganese, 1.74 per cent.

‡ Nominal composition.

The gamma-phase iron-nickel alloys are characterized by high initial permeability, especially after rapid cooling from about 930°C. (1705°F.). Schulze proved, however, that magnetostriction of these alloys is independent of preliminary treatment, and that there is no simple relationship between the higher initial permeability and magnetostriction. This is likewise true of magnetostriction and intensity of magnetization, as is shown by Fig. 234, and of magnetostriction and electric resistivity.

The magnetostriction of alpha-phase (irreversible) alloys is decidedly influenced by thermal treatment, especially in the concentration range in which gamma phase is retained easily

upon quenching. No further statement can be made because of the excessively large number of possible states.

Further measurements by Schulze on alloys prepared by the vacuum melting of electrolytic iron and electrolytic nickel yielded the results given in Table 61. The only difference between these data and those obtained on the first series of alloys

Fig. 234.—Magnetostriction of iron-nickel alloys; variation of magnetostriction with intensity of magnetization. (*Schulze.*[256])

is that, as a consequence of higher purity, they are of smaller magnitude.

138. Relationship between Magnetostriction and Magnetization.—It was shown by Schulze[466] that, as saturation is approached, magnetostriction is proportional to the square of the magnetization, or

$$\Delta l/l = C(I^2 - I_0^2)$$

where C is a constant of the material and I_0 depends upon the

FIG. 235.—Magnetostriction of iron-nickel alloys and polycrystalline nickel as dependent on the square of intensity of magnetization.   (*Schulze.*[466])

FIG. 236.—Magnetostriction of a 63 per cent nickel iron-nickel-alloy single crystal, in the [100] direction, as dependent on the square of intensity of magnetization.   (*Schulze*[466] *after Lichtenberger.*)

internal strain of the material. This relationship was confirmed by Kirchner.[567]

In Fig. 235, some of Schulze's magnetostriction values for polycrystalline nickel and iron-nickel alloys are plotted against the square of the relative intensity of magnetization. In Fig. 236, Lichtenberger's data (see next section) on magnetostriction in the [100] direction of a single crystal of a 63 per cent nickel alloy are plotted against the square of the intensity of magnetization.

TABLE 61.—MAGNETOSTRICTION OF VACUUM-MELTED ALLOYS
OF ELECTROLYTIC IRON AND ELECTROLYTIC NICKEL*

Field strength, oersteds	Magnetostriction, $\Delta l/l \times 10^6$					
	Nickel, per cent†					
	100	90	81	75	65	55
5.6	−4.37					
11.2	−7.84	−4.98	0.75	3.17	6.41	7.09
22.5	−13.80	−8.75	1.21	4.75	9.13	9.88
33.8	−16.89					
45.1	−19.08	−10.78	1.51	....	10.26	12.97
67.6	−21.34	−11.31	1.73	6.49	10.56	13.80
90.2	−22.93	−11.61	1.73			
112.8	−23.91	−11.84	1.73	6.86	11.01	14.18
141.0	−24.81					
169.2	−25.34	−12.22	1.73	7.01	11.46	14.18
225.6	−26.01					
282.0	−26.40					

* Schulze.[288]

† The nickel contained 0.81 per cent cobalt, 0.13 per cent iron, 0.04 per cent copper, and about 0.01 per cent carbon.

139. Magnetostriction of Single-crystal Iron-nickel Alloys.— Lichtenberger[421] examined about 40 fairly pure cylindrical single-crystal specimens of gamma-phase alloys. In general, the orientation of the crystals was random, although the [100] orientation appeared in several. In order to correlate the data from intermediate orientations, the formula of Akulov[289] was used:

$$f = \cos^2 \alpha_1 \cos^2 \alpha_2 + \cos^2 \alpha_2 \cos^2 \alpha_3 + \cos^2 \alpha_1 \cos^2 \alpha_3$$

where f is the orientation factor and α_1, α_2, and α_3 are the angles between the axis of the specimen and the crystal axes.

Data are given in Table 62.   These are best shown as saturation magnetostriction plotted against orientation factor, as in

TABLE 62.—MAGNETOSTRICTION DATA ON SINGLE-CRYSTAL IRON-NICKEL ALLOYS*

Specimen, No.	Nickel, per cent	Orientation	Orientation factor, f	Magnetostriction, $\Delta l/l \times 10^6$	Saturation magnetization, $4\pi I_\infty$	Coercive force, oersteds	Magnetization: D = difficult, E = easy
60a	33	[103]	0.090	−0.6	13,000?	0.2?	D
60b	33	[100]	0.000	−0.6	8,000	0.25	?
60b	33	.....	......	−1.4			
60b	33	.....	......	−0.55			
60c	33	[236]	0.222	5.4	11,000	0.4	D
60c	33	.....	......	6.5			
60d	33	[122]	0.296	16.8	12,000	0.25	D
60d	33	.....	......	15.4			
63a	38	[156]	0.244	17.5	14,800	0.3	D
63b	38	[100]	0.006	−6.6	14,000	0.35	?
76a	44	[058]	0.200	13.4	15,200	0.7	D
76b	44	[127]	0.055	−0.3	16,800	0.6	E
76b	44	.....	......	−1.0	✦		
76c	44	[456]	0.314	23.0	18,000	0.35	D
76c	44	.....	......	25.0			
76c	44	.....	......	36?			
76d	45.4	[016]	0.030	0	16,500	0.6	E
76d	45.4	.....	......	−1.5			
76d	45.4	.....	......	−0.8			
76e	44	[115]	0.085	−0.5			
59a	48	[017]	0.0255	4.7	15,000	0.45	E
61a	53.5	[100]	0.000	15	17,200	0.03	E
61a	53.5	.....	......	11?			
61b	53.5	[125]	0.115	16	16,800	0.24	?
61b	53.5	.....	......	18			
65a	59.5	[126]	0.128	17.5	14,000	0.03	E
65a	59.5	.....	......	20			
65b	59.5	[236]	0.202	23.4	14,900	0.18	?
65b	59.5	.....	......	19.4	14,500		
66a	63	[122]	0.297	15.0	15,000	0.4	E
66b	63	[100]	0.006	20.5	15,700	0.45	?
67a	67.5	[237]	0.1815	14			
67b	67.5	[012]	0.153	13	14,700	0.25	D
87a	71	[100]	0.000	20	13,400	0.09	E
87b	71	[018]	0.015	17.5	14,200	0.2	D
87c	71	[110]	0.240	10.5	14,500	0.1	E?
88a	77.5	[100]	0.038	9.5	12,900	0.05	D?
89a	77	[012]	0.155	1?	13,800	0.03	D?
15a	80?	[114]	0.118	7.2	9,600	0.1	E?
20a	80?	[112]	0.281	1.6	10,200	0.1	
78a	82	[011]	0.259	0.9	11,000	0.1	E
78b	82	[125]	0.140	4.7	12,600	....	D?
70a	82.5	[110]	0.236	1.1	11,900	0.35	E?
72a	82.5	[113]	0.194	3.9	11,300	0.1	D
81a	85.5	[118]	0.050	−4	10,500	0.2	D
81a	85.5	.....	......	−6			
81b	84	[100]	0.010	0.3	11,500	0.23	D
75a	90.5	[447]	0.288	−8.2	9,400	0.35	E?
75b	90.5	[233]	0.314	−7.9	9,600	0.2	E?
79a	91	[135]	0.207	−10	8,000	0.17	D?
79b	91	[239]	0.140	−12			
79c	91	[157]	0.224	−13	8,800	....	D?
82a	100	[145]	0.242	−30	7,200	0.26	D
82b	100	[100]	0.000	−45	6,600	1.4	D

*Lichtenberger. [421]

Fig. 237, which yields a straight line for each composition.   From 33 to about 59 per cent nickel the slope is positive; from about 59

to 80+ per cent nickel the slope is negative; and from 81+ to 100 per cent nickel the slope is again positive.

From the $(\Delta l/l)_\infty$ values for $f = 0$ [100], $f = 0.250$ [110], and $f = 0.333$ [111] saturation magnetostriction in these three principal directions can be plotted, as is done in Fig. 238. The curves are seen to intersect at about 59 and 85.5 per cent nickel. The latter value can be considered fairly accurate, because speci-

FIG. 237.—Variation of magnetostriction with composition. (*Lichtenberger.*[(421)])

men 81a contained 85.5 per cent nickel by check analysis. It is to be observed that these intersections mark isotropic magnetostriction.

McKeehan[(500)] noted that the equation of the form quoted by Lichtenberger fits the data "rather well." It is

$$\left(\frac{\Delta l}{l}\right)_\infty = \Delta_0 + f\Delta_{22}$$

where Δ_0 and Δ_{22} are constants and f, as before, is the orientation

factor. The evaluated constants are given in Table 63. The quantity Δ_{22} is positive when saturation magnetostriction for the [111] direction is algebraically greater than that for the [100] direction.

140. Volume Magnetostriction of Single-crystal Iron-nickel Alloys.—The specimens of Lichtenberger (page 323) were used by

FIG. 238.—Variation of magnetostriction with the orientation factor. (*Lichtenberger.*[421])

von Auwers[440] to determine volume magnetostriction of single-crystal alloys. It was found that (as is true of polycrystalline alloys) $\Delta v/v$ in weak fields is small or negligible and that it is a linear function of field strength beyond approximate saturation. Crystal orientation with respect to axis of magnetization was found to have no effect (beyond approximate saturation). The actual value of $\Delta v/v$, however, did depend upon orientation because of varying values of field strength required to induce

TABLE 63.—VALUES OF Δ_0 AND Δ_{22} FROM LICHTENBERGER'S DATA*

Nickel, per cent	$\Delta_0 \times 10^6$	$\Delta_{22} \times 10^6$
100	−45	+63
91	−17	+28.5
85.5	−5	0
82	+10	−34.5
80	+11	−33
71	+18	−31.5
63	+21	−21
59	+18	+12
53	+13	+33
44	−5	+97.5
38	−7	+99
33	−2.5	+61.5

* McKeehan.[500]

saturation. Several single crystals of identical composition but different orientation therefore yield, beyond saturation, parallel $\Delta v/v$ lines. As is true of polycrystalline alloys, composition was found to be the largest factor which affects volume magnetostriction; this becomes especially clear when the slope

$$\alpha = \frac{d(\Delta v/v)}{dH}$$

is plotted against nickel content, as in Fig. 239. Shown also are values computed from Masiyama's data (see page 329) on polycrystalline alloys; it is to be seen that agreement is only fair and that these points do not show conclusively the minimum at about 63 per cent nickel.

Figure 239 seems to admit the possibility of the small positive value (0.2×10^{-9}) for $\frac{d(\Delta v/v)}{dH}$ found by Kornetzki[531] for nickel beyond approximate saturation, although he found $\Delta v/v$ to be negative in sign in weak fields for one specimen.

141. Correlation of Single- and Polycrystalline Properties.— A formula for approximate computation of properties of ferromagnetic substances which depend upon magnetization was derived by Akulov.[329] Such properties are magnetostriction, change of electric resistance, and stored energy. The form

FIG. 239.—Variation with composition of the slope of the volume magnetostric-
tion–field strength curve.

FIG. 240.—Comparison of observed and computed polycrystalline saturation
magnetostriction.

suitable for computation of magnetostriction at saturation of polycrystalline metal is

$$\Delta l = \frac{1}{5}\left(\frac{2\Delta l}{l_{[100]}} + \frac{3\Delta l}{l_{[111]}}\right)$$

Values computed from Lichtenberger's data are compared with those observed on polycrystalline alloys in Fig. 240. It appears that there is, as yet, no wholly satisfactory means of correlation, although this might be possible if all orientations in polycrystalline material were equally probable.

142. Transverse and Volume Magnetostriction.—Longitudinal $(\Delta l/l)_P$, transverse $(\Delta l/l)_N$, and volume $(\Delta v/v)$ magnetostriction

Fig. 241.—Variation of transverse magnetostriction with field strength. (*Masiyama.*[390])

of vacuum-melted alloys of electrolytic iron and nickel to which 0.5 per cent manganese was added were measured by Masiyama.[390] Specimens, in the form of ellipsoids of revolution, seem to have been prepared carefully. Since results on longitudinal magnetostriction are in fair agreement with the data already reported, they are not repeated here.

Masiyama's data on transverse magnetostriction, however, are the only directly observed values on $(\Delta l/l)_N$ of iron-nickel alloys in existence. They are shown as a function of field strength in Fig. 241. For iron the effect was not observable in fields of less than 400 oersteds; expansion occurred in fields of higher strength. Alloys containing 30 and 90 per cent nickel and the electrolytic nickel also expanded, but the remaining alloys contracted. Contraction of the 80 per cent nickel alloy

Fig. 242.—Variation of transverse magnetostriction with composition. (*Masi-yama*.[390])

Fig. 243.—Variation of volume magnetostriction with field strength. (*Masi-yama*.[390])

was the smallest. Transverse magnetostriction as a function of composition is given in Fig. 242.

Transverse magnetostriction of iron, nickel, and iron-nickel alloys was computed by Esau[378] from the data of Nagaoka and

FIG. 244.—Variation of volume magnetostriction for various field strengths with composition. (*Masiyama*.[390])

Honda[53] on longitudinal and volume magnetostriction. For the computation, he used the formula (for cylindrical specimens)

$$v + \Delta v = \frac{(l_N + \Delta l_N)^2}{4} \pi (l_P + \Delta l_P)$$

where v is volume, l_N is the diameter, and l_P is the length. The resulting values for alloys are in reasonably good agreement with Masiyama's data, as shown by Fig. 242; the agreement for

iron and nickel is so close that the points are distinguished with difficulty.

The volume magnetostriction as a function of field strength of iron-nickel alloys is summarized in Fig. 243. The volume change of iron is small; it expands in fields of strength up to about 300 oersteds, contracts from about 300 to 750 oersteds, and again expands in fields of higher strength. Nickel contracts in fields of all strengths. Alloys containing 10 to 90 per cent nickel expand in fields of all strengths. For nickel contents greater than 20 per cent, expansion is very nearly a linear function of field strength. Volume magnetostriction as a function of composition for fields of 250, 500, and 1000 oersteds is shown in Fig. 244. The tremendous increase of volume in the vicinity of 30 per cent nickel (previously observed by Nagaoka and Honda[53]) is without explanation.

Since volume magnetostriction is the combined effect of longitudinal and transverse magnetostriction, Masiyama compared values computed from

$$\frac{\Delta v}{v} = \left(\frac{\Delta l}{l}\right)_P + 2\left(\frac{\Delta l}{l}\right)_N$$

with the observed values and found rough agreement.

B. MAGNETOSTRICTION OF COMPLEX ALLOYS. OTHER EFFECTS

There is relatively little information on ternary alloys of which iron and nickel are two components. This is likewise true of mechanomagnetic effects other than magnetostriction. However, as was stated before, these effects are unimportant practically, with the possible exception of the effect of magnetization on elastic constants.

143. Magnetostriction of Iron-nickel-chromium Alloys.— Dean[335] reported magnetostriction measurements on some iron-nickel-chromium alloys, but their form is not suitable for numerical reproduction. He found, however, that magnetostrictively active alloys are confined to a relatively small portion of the concentration triangle, mostly along the iron-nickel side.

144. Magnetostriction of Iron-nickel-beryllium Alloys.— According to Dietsch,[377] the magnetostriction of an iron-nickel

alloy containing 77 per cent nickel was not changed markedly by the addition of 0.5 and 1 per cent beryllium.

145. Volume Magnetostriction of Iron-nickel-cobalt Alloys.— The volume magnetostriction of 14 polycrystalline iron-nickel-cobalt alloys was determined by von Auwers.[440]   Values for a field strength of 1100 oersteds are summarized in Fig. 245.   To be noted is the fact that the perminvar composition (about 45 per

Fig.   245.—Volume   magnetostriction   of   iron-nickel-cobalt   alloys.   (*Von Auwers.*[440])

cent nickel, 25 per cent cobalt, remainder iron) lies in a valley representing small volume magnetostriction.

146. Magnetostriction of Iron-nickel-copper Alloys.—Alloys having relatively low magnetostriction were investigated by von Auwers and Neumann.[513]   Copper addition to iron-nickel alloys shifted the composition of minimum magnetostriction to lower nickel contents; this was true for the volume effect as well as for the longitudinal effect.

147. Effect of Tension on Magnetization (the Villari Effect).—
The magnetostriction of two alloys, containing 35 and 45 per
cent nickel, under constant tension was measured by Honda and
Shimizu.[42] They found that, compared with other ferro-
magnetic materials, the effect of tension was large; increased
tension decreased longitudinal magnetostriction. Tension of
1.4 kg. per sq. mm. (1990 lb. per sq. in.) decreased the magneto-
striction of the 45 per cent alloy to one-half the value for no
tension. Results for the 35 per cent nickel alloy were similar,
although different in magnitude, as is shown by Fig. 246.

FIG. 246.—Effect of tension on magnetostriction for a field strength of 100
oersteds. (*Honda and Shimizu.*[42])

Alloys, in the form of wires, of composition in the permalloy
region, were studied under tension up to 10,000 lb. per sq. in. and
under magnetization up to saturation by Buckley and McKee-
han.[209] The 81 per cent nickel alloy was nearly indifferent to
tension. Alloys containing less nickel were more easily magnet-
ized under tension and exhibited less hysteresis; the 84 per cent
nickel alloy was harder to magnetize and had greater hysteresis
under tension. Saturation magnetization, however, was inde-
pendent of tension.

The effect of tension, compression, and torsion on the longitudi-
nal magnetostriction of nickel and iron-nickel alloys containing

15 and 50 per cent nickel was investigated by Kirchner.[567] Tension decreased the saturation magnetostriction of the two alloys, whereas compression increased it. The effect for nickel was the reverse in accordance with the relation

$$\left(\frac{\Delta l}{l}\right)_{te} = \frac{3}{2}\left(\frac{\Delta l}{l}\right)_{no\ tension}$$

This relation was valid for the alloys if compression was substituted for tension. The effect of torsion was to reduce saturation magnetostriction to a limit of about 75 per cent of its initial value.

Fig. 247.—The variation with temperature of the saturation magnetostriction of nickel. (*Döring.*[559])

148. Effect of Hydrostatic Pressure on Magnetization.—A series of iron-nickel alloys was subjected by Steinberger[469] to pressures up to 12,500 kg. per sq. cm. The following effects were noted, excepting the 30 per cent nickel alloy: (1) The first application of pressure caused a relatively large change of magnetization, usually a decrease, followed by incomplete recovery upon release of pressure. (2) The same curve, or hysteresis loop— and hysteresis often appeared—was retraced upon subsequent applications of pressure, provided that the previous maximum pressure was not exceeded. (3) The pressure effect was positive or negative, depending on the field strength. (4) The field strength at which the change of sign of the pressure effect occurred depended on (*a*) the temperature of measurement, (*b*) the amount of cold work, and (*c*) the annealing process.

FIG. 248.—Influence of magnetization on the modulus of elasticity of iron-nickel alloys.   (*Nakamura.*[535])

FIG. 249.—The effects of temperature and magnetization on the modulus of elasticity of an iron-nickel alloy containing 93 per cent nickel.   (*Engler.*[617])

149. Effect of Temperature on Magnetostriction.—The variation of saturation magnetostriction with temperature is illustrated by Fig. 247, obtained by Döring.[559] This curve, although for nickel, is probably characteristic of iron-nickel alloys as well. Its similarity to magnetization-temperature curves is marked.

Fig. 250.—The effects of temperature and magnetization on the modulus of elasticity of an iron-nickel alloy containing 78.5 per cent nickel. (*Engler.*[617])

150. Influence of Magnetization on Modulus of Elasticity.— The modulus of elasticity of ferromagnetic substances is ordinarily changed by magnetization; this is known as the ΔE effect. Data obtained by Nakamura[535] by a magnetostriction method are given in Fig. 248. Nickel exhibited the greatest $\Delta E/E$ effect, the change at saturation magnetization being 17 per cent. The effect for an alloy probably containing 78 per cent nickel was found by von Auwers[440] to be small, not more than 1.4 per cent. This is in agreement with the finding of Siegel and Rosin[580] that the effect is very small in alloys containing 81 per cent nickel.

FIG. 251.—The effects of temperature and magnetization on the modulus of elasticity of an iron-nickel alloy containing 42 per cent nickel.   (*Engler*.[617])

FIG. 252.—The ΔE effect at several temperatures in an alloy containing 93 per cent nickel.   (*Engler*.[617])

The ΔE effect as a function of temperature was investigated by Engler,[617] who followed Kersten[454] in defining the effect as $\Delta E = E_\infty - E$, where E_∞ is the modulus of elasticity in the magnetically saturated state and E is the modulus in the unmagnetized state. Results for alloys containing 93, 78.5, and 42 per cent nickel are given in Figs. 249 to 251. Figure 251 shows clearly that the temperature coefficient of the 42 per cent nickel alloy was positive for all temperatures up to the magnetic inversion. Hysteresis of the ΔE effect at several temperatures in the 93 per cent nickel alloy is shown by Fig. 252; these curves are similar to those for the other alloys.

Kersten[454] and others have attempted to compute the ΔE effect from magnetic quantities and internal stress. Such methods lead to results not wholly in agreement with observed values, but the picture seems to be correct in its essentials.

C. AUTHOR'S SUMMARY

1. Most of the available information on mechanomagnetic effects is on magnetostriction—the change of dimensions of a ferromagnetic body upon magnetization. Longitudinal magnetostriction, in the direction of the magnetic field, may be positive or negative; some substances elongate in fields of certain strength and contract in fields of other strength; other substances elongate in fields of all 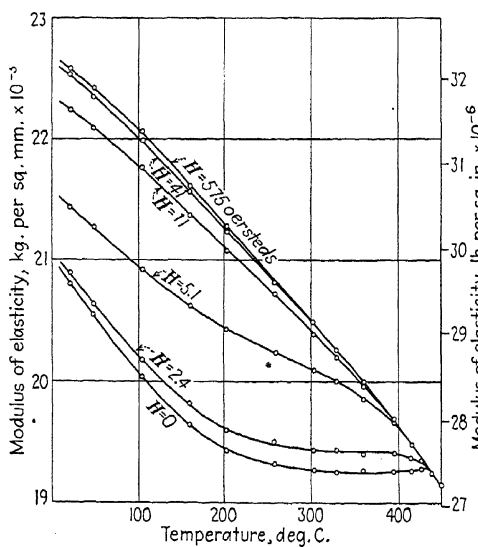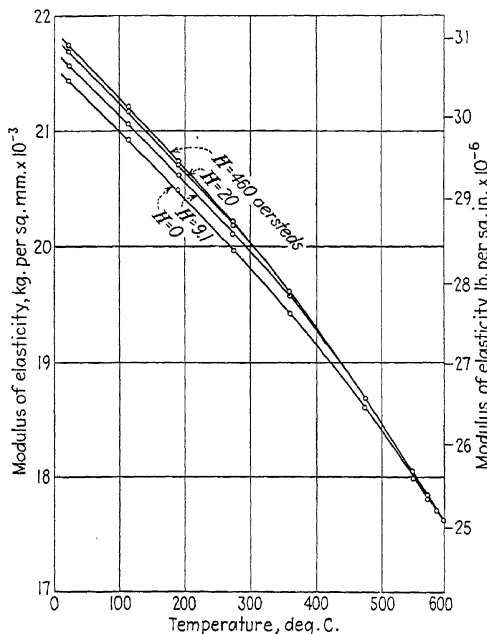strengths, still others contract in fields of all strengths. Transverse magnetostriction, in the direction normal to that of the magnetic field, behaves similarly. The sign of the change of dimensions is ordinarily different in the two directions, consequently the change of volume upon magnetization is ordinarily small as compared with change of length. In a few substances, however, the sign is the same in both directions; in this event, the change of volume is relatively large.

2. When subjected to a magnetic field, iron at first elongates—then, in fields of higher strength, contracts. Nickel contracts in fields of all strengths. Of the iron-nickel alloys, those containing more than about 30 per cent nickel are of the most interest. Up to about 81 per cent nickel, the magnetostriction of these (gamma-phase) alloys is positive; from about 81 to 100 per cent nickel, it is negative.

3. Gamma-phase iron-nickel alloys are characterized by high initial permeability, especially after rapid cooling from about

930°C. (1705°F.). A relationship between initial permeability and magnetostriction leads to results that agree fairly well with the observed.

4. The magnetostriction of alpha-phase (irreversible) alloys is greatly influenced by thermal treatment, but definite statement is made difficult by the large number of possible mixtures of alpha and gamma phases.

5. The initial slope of curves representing longitudinal magnetostriction versus magnetization is zero; as magnetization approaches the saturation value it is proportional to the square of magnetization.

6. Magnetostriction of single-crystal iron-nickel alloys depends upon their orientation, although the curves representing magnetostriction in the principal directions, [100], [110], and [111], intersect at about 59 and 85.5 per cent nickel. Composition is the greatest factor in determining the magnitude of magnetostriction.

7. The volume magnetostriction of single-crystal alloys is negligible in weak fields and a linear function of field strength in fields higher in strength than that required to induce saturation.

8. Proposed correlations of single- and polycrystalline properties that depend upon magnetization are not wholly satisfactory.

9. Computed values of transverse magnetostriction (from longitudinal and volume magnetostriction) are in reasonably good agreement with the observed.

10. The volume magnetostriction of polycrystalline iron-nickel alloys rises to a sharp maximum in the vicinity of 30 per cent nickel.

11. There are few data on complex alloys containing iron and nickel. Those which show that perminvar alloys exhibit relatively small volume magnetostriction are noteworthy.

12. The change of sign of magnetostriction of iron-nickel alloys at about 81 per cent nickel has been verified by studying the effect of tension on magnetization.

13. The elastic constants, such as the modulus of elasticity, of ferromagnetic substances are ordinarily changed by magnetization. These are usually regarded as results of magnetostrictive changes of dimensions. The few data on iron-nickel alloys indicate that the change with magnetization of the modulus of elasticity passes through a minimum near 80 per cent nickel.

CHAPTER X

ELECTRIC PROPERTIES

Electric Properties of Iron-nickel Alloys—Electric Properties of Complex Alloys—Author's Summary

The electric property of iron-nickel and associated alloys of most interest is resistivity, or, as it is sometimes known, specific resistance. This is true for various reasons. First, the reversible gamma-phase alloys include highly important magnetic materials, and the resistivity of such materials is important because of its control over eddy currents. Second, iron and nickel are common components of alloys used for electric heating devices.

The resistivity of metals depends upon a number of factors, especially upon purity and thermal and mechanical history. Among the less common factors is, for example, an external magnetic field. Some of these effects seem to be useful only as guides in the development of the theory of metallic substances, but it is not uncommon for practical usefulness to be found also. In addition to the review of data on resistivity, those on thermal electromotive force are examined.

A. ELECTRIC PROPERTIES OF IRON-NICKEL ALLOYS

First to be considered are electric resistivity and its allied properties of iron-nickel alloys, either of high purity, or of purity such as results from the alloying of ordinary iron and nickel.

151. Electric Resistivity of Iron-nickel Alloys.—It is characteristic of solid solutions that their electric resistivity is greater than that of the pure components. Ordinarily, the first increments of solute cause the greatest increase of resistivity. This is clearly true of iron-rich alloys of iron and nickel, as is shown by Fig. 253. This diagram does not contain all available information on the subject, but it does include data that depict most reliably the variation of electric resistivity ·as a function of

341

Fig. 253.—The electric resistivity (20°C.) of iron-nickel alloys.

composition. Attention is directed especially to the results of Broniewski and Smolinski,[443] Sizoo and Zwikker,[324] and Yensen.[157] Yensen's data are especially useful for determining the course of the curve in the alpha-phase region. In all three investigations, reasonably pure materials were used and the methods seemingly were capable of producing self-consistent results.

Because of the alpha-gamma transformation, scatter is to be expected in the region containing the alloys with approximately 10 to 30 per cent nickel; this expectation is amply fulfilled, consequently it seems best to restrict definite conclusions concerning alpha-phase alloys to those containing less than 10 per cent nickel. It appears, then, that the resistivity at 20°C. increases from about 9.6 microhm-cm. for iron to about 27 microhm-cm. at 10 per cent nickel and that the curve is convex upward, in agreement with the usual behavior.

The behavior of nickel-rich alloys is not so clear. Unquestionably the major portion of the curve for gamma-phase alloys is convex downward—perhaps all of it—and this is unusual behavior. The data indicate that the curve may be convex upward in the vicinity of 100 per cent nickel, but this has not been established definitely. Numerically the data seem to fall into two groups, the smaller for a given nickel content being those of Broniewski and Smolinski and of Sizoo and Zwikker. (These investigators reported results for 0°C., but correcting them to 20°C. would raise the curve too slightly to affect the argument.) The other group contains the values of Burgess and Aston,[81] Boudouard,[92] Ingersoll *et al.*,[152] Würschmidt,[226] and Ribbeck.[241] Perhaps the first group is the closer approximation to the truth for high-purity alloys; the second may be taken as an indication of the resistivity of ordinary materials.

Definite statement about the transition region, in the vicinity of 30 per cent nickel, is difficult. Evidence seems to point to the fact that the resistivity of gamma-phase alloys rises to 80 to 90 microhm-cm., then falls as the amount of coexisting alpha phase increases.

By way of completeness, a few other investigators of electric resistivity may be cited. First credit seemingly goes to Hopkinson,[9] who, as early as 1889, published determinations on a

25 per cent nickel alloy. It is of historical interest that they were 72 microhm-cm. for the "non-magnetizable condition" and 52 microhm-cm. for the "magnetizable condition." These values are as good as any available today. Guillaume[25,26] determined resistivities in connection with his investigations, but most of the alloys were irreversible. In the first comprehensive paper on iron-nickel alloys ever published, Hadfield[31] stated that the resistivity of iron is increased rapidly by the addition of nickel. Quantitative data on Hadfield's alloys were given by Barrett.[38] Benedicks[66,120,126] was interested in meteorites and in empiric relations between resistivity and composition. Waterhouse[64] probably was the first to measure the resistivity of low-nickel high-carbon alloys. Honda[157] investigated 17 alloys containing (nominally) up to 95 per cent nickel, but the results deviate rather markedly from those given in Fig. 253. Portevin[76] determined the resistivity of essentially iron-nickel-carbon alloys containing up to 30 per cent nickel and 0.1, 0.2, and 0.8 per cent carbon. Redeterminations cn the same alloys by Boudouard[92] were not wholly in agreement, but the divergence was ascribed by Portevin[167] to difference of heat treatment. Enlund[135] and Campbell[141] investigated empiric relations also.

152. Effect of Temperature on Electric Resistivity.—Results of the several investigations of electric resistivity of iron-nickel alloys at various temperatures are in fair agreement. Ingersoll and his students[152] showed the maximum at about 30 per cent nickel at room temperature to persist to at least 700°C. The most extensive investigation was that of Ribbeck;[241] unfortunately his alloys were not the purest obtainable, e.g., his nickel was of the 98 per cent grade, and this is reflected by the deviations from results on high-purity alloys at room temperature. Since, however, Ribbeck's data are probably representative of the somewhat less pure alloys, they are reproduced in full in Table 64. Similar results in graphical form were reported by Chevenard.[271] A few data were given also by Gossels,[301] although his interest was primarily in irreversible alloys, as was that of Anastasiadis and Guertler.[371]

153. Temperature Coefficient of Electric Resistivity of Iron-nickel Alloys.—Of the possible definitions of temperature coefficient of electric resistivity, that in common use is

mean temperature coefficient $\alpha_{t_1-t_2} = \dfrac{1}{R_0} \cdot \dfrac{R_{t_2} - R_{t_1}}{t_2 - t_1}$

where R_{t_2}, R_{t_1}, and R_0 are the resistivities at temperatures t_2, t_1, and 0°C. respectively. The usual temperature limits are 0 and 100°C. Data on this coefficient are collected in Fig. 254. Considering first the iron-rich alloys, it appears reasonable to conclude that the coefficient for iron (about 0.0065 per °C.)

FIG. 254.—The mean temperature coefficient (0 to 100°C.) of resistance of iron-nickel alloys.

is reduced rapidly to about 0.002 by the presence of 10 per cent nickel. From 10 to 30 per cent nickel the points are scattered badly, but this is to be expected because of the alpha-gamma transformation; nevertheless, it can be concluded provisionally that the coefficient lies in a rather broad band including 0.002 per °C.

Graphical representation of the temperature coefficients for gamma-phase alloys leads to the unexpected result that the data mostly fall into two well-defined groups. The first contains those of Sizoo and Zwikker[324] and of Broniewski and Smolinski;[443] the second group, shown by the broken line in Fig. 254,

TABLE 64.—THE ELECTRIC

Composition, per cent		Electric resistivity, microhm-cm., at									
Ni	C	−185°C.	−78°C.	0°C.	50°C.	100°C.	150°C.	200°C.	250°C.	300°C.	350°C.
0	0	0.8	5.0	8.9	11.6	14.6	18.2	22.2	26.4	31.0	35.2
5.5	0.09	19.0	23.2	26.7	29.8	33.0	36.3	40.0	44.0	48.9	53.4
											53.0
9.5	0.12	21.3	27.4	32.7	34.8	37.6	41.3	45.6	50.7	55.5	62.0
				29.9	32.6	35.7	39.1	42.8	46.7	51.0	55.8
9.55	0.59	28.9	35.1	44.0	50.8	60.0	70.8	78.0	85.0	90.5	89.4
				37.2	40.4	43.6	46.9	50.3	53.8	56.6	61.1
14.7	0.06	26.6	31.6	37.0	39.5	43.7	50.6	62.1	84.0	91.2	95.2
				33.7	36.7	39.9	43.5	47.4	51.5	55.9	60.3
19.2	0.03	27.0	33.9	39.5	47.8	64.5	84.7	88.3	92.3	95.0	97.5
				39.0	42.5	46.3	50.3	54.5	59.0	63.7	68.0
24.5	0.16	33.2	50.5	78.6	82.4	86.0	89.4	92.7	95.6	98.3	99.6
				40.8	44.0	47.7	51.8	56.1	60.6	65.1	69.8
25.0	0.07	32.0	39.4	66.0	78.5	86.5	90.5	93.6	96.8	99.5	101.9
				40.0	44.1	47.9	52.1	56.2	60.7	65.4	70.0
27.7	0.31	38.1	80.0	84.6	88.1	91.3	94.2	97.0	99.7	102.1	104.7
				49.3	52.7	57.2	61.6	66.2	70.8	75.1	79.9
29.15	0.18	34.5	79.0	84.7	88.0	91.0	93.9	96.6	99.1	101.3	103.6
				43.0	47.0	51.4	55.9	60.6	65.6	70.8	76.1
29.9	0.18	47.1	80.3	85.2	88.5	91.6	94.3	96.9	99.4	101.8	104.2
				60.0	64.0	68.2	72.3	76.3	80.3	84.0	96.4
35.2	0.13	47.1	63.8	73.1	80.5	86.7	91.8	96.0	99.4	101.9	104.8
44.6	0.04	22.5	37.4	48.6	57.3	66.1	75.0	82.9	89.6	96.2	101.6
50.3	0.05	24.7	36.0	44.8	51.7	58.8	66.5	74.3	81.5	88.7	95.1
56.5	0.06	21.9	30.1	38.1	44.0	50.5	57.4	64.4	71.5	78.6	86.4
65.0	0.03	17.5	23.9	29.1	33.5	39.0	44.8	50.8	57.3	64.3	71.0
73.8	0.01	11.2	16.0	21.6	25.9	30.5	35.3	40.5	46.3	52.5	58.3
85.35	0.03	7.3	11.9	15.9	19.0	22.2	25.7	29.6	33.7	38.6	42.9
98.17	0.06	3.5	6.9	9.7	11.8	14.0	16.6	19.5	22.8	26.6	31.8

* Ribbeck.[241]

represents fairly well the data of Ribbeck[241] and of Schulze.[508] (The data of Ellis, quoted by Bridgman,[269] are excluded from consideration.) There is no obvious explanation of the divergence of the two groups; however, the alloys of Sizoo and Zwikker seem to have been of fairly high purity (they were melted under hydrogen from 99.9 per cent iron and 99.6 per cent nickel). If this fact is somehow responsible, it follows, of course, that the alloys of Broniewski and Smolinski were of high and comparable purity. The suggestion is not impossible, because some of Ribbeck's alloys contained well over 1 per cent manganese and others contained more than 0.1 per cent carbon. Schulze's alloys contained less carbon (less than 0.03 per cent) but 0.4 to 1.7 per cent manganese.

There is some information on the temperature coefficient defined by

$$\alpha_t = \frac{1}{R_0} \cdot \frac{dR}{dt}$$

Ribbeck,[241] for example, reported coefficients for 50° intervals

RESISTIVITY OF IRON-NICKEL ALLOYS*

Electric resistivity, microhm-cm., at

400°C.	450°C.	500°C.	550°C.	600°C.	650°C.	700°C.	750°C.	800°C.	850°C.	900°C.	950°C.	1000°C.
40.9	47.0	53.6	60.7	68.1	76.1	85.5	96.0	105.6	110.4	113.6	115.3	116.6
58.5	64.5	71.3	79.4	95.0	105.6	108.5	110.8	113.0	115.0	116.7	118.4	119.2
57.5	62.9	68.7	74.2	81.4	89.0	101.0	110.3					
70.6	89.5	99.9	102.5	104.8	107.1	109.4	111.2	103.1	104.8	111.6	113.2	114.6
60.6	65.6	70.9	86.4	82.8	91.0	106.8						
94.5	98.4	101.8	105.6	108.6	110.8	112.8	114.9	116.9	118.4	119.9	121.2	122.5
65.6	70.5	75.5	81.0	87.4	106.9							
98.2	101.0	103.2	105.8	108.1	110.5	112.4	114.3	115.9	117.5	119.1	120.6	122.1
64.8	69.7	75.7	83.6	93.1	115.0							
99.9	102.5	105.0	107.5	109.6	111.2	113.0	114.9	116.5	118.0	118.9	120.3	121.5
73.5	78.8	83.8	90.6	108.7								
101.8	104.1	106.4	108.5	110.6	115.9	113.2	114.9	116.0	117.2	118.5	119.5	120.4
74.9	80.3	86.3	101.0									
104.0	106.2	108.4	110.3	112.0	113.6	115.3	116.8	118.3	119.6	120.8	121.9	122.8
75.3	81.5	89.3	101.5	110.9								
106.9	109.0	110.9	112.4	114.2	115.8	117.4	119.0	120.4	121.6	122.9	124.2	125.6
84.8	90.5	100.0										
105.8	107.6	109.7	111.6	113.3	114.9	115.5	116.9	119.4	120.8	121.9	122.9	123.9
82.5	91.5	102.0										
106.4	108.3	110.2	111.8	113.4	114.9	116.1	117.3	118.6	119.9	121.3	122.5	123.6
90.1	96.0	108.0										
106.8	107.6	110.3	111.8	113.1	113.9	115.5	116.6	117.9	119.0	120.3	121.2	122.1
105.5	107.8	110.2	111.6	113.0	114.0	115.5	116.5	117.7	118.9	120.0	121.1	122.2
101.4	107.3	111.0	112.7	114.0	115.5	116.3	117.2	118.1	119.0	119.9	120.9	121.9
93.7	101.2	107.9	112.5	114.3	115.2	116.0	117.0	118.0	119.0	120.0	120.9	121.8
77.4	85.0	91.9	100.8	106.0	107.6	108.5	109.4	110.2	111.0	111.8	112.9	113.8
65.1	72.2	80.0	88.4	96.1	101.2	103.0	104.0	104.9	105.6	106.4	107.1	107.9
48.3	54.3	62.3	65.7	67.5	69.7	71.0	72.5	73.9	75.3	76.8	78.2	79.5
34.3	36.2	38.0	39.6	41.3	42.9	44.3	46.0	47.0	49.2	50.4	51.5	53.1

for the range 0 to 1000°C.; these are reproduced in Table 65. Because of the aforementioned two groups of data on mean coefficients for the 40 to 90 per cent nickel region, the reliability of Ribbeck's data is unknown since his values for mean coefficients seem to fall in the less probable group for high-purity alloys. However, these data are well able to show the influence of temperature on the coefficient. Others given (graphically) by Chevenard,[271] are in fair agreement with those of Ribbeck, consequently are not reproduced. Additional points shown in Fig. 254, but not hitherto mentioned, are those of Ingersoll *et al.*[152] and of Jordan and Swanger.[343]

154. Effect of Pressure on Electric Resistance.—The effect of pressure up to 12,000 kg. per sq. cm. on the electric resistance of iron-nickel alloys was determined by Bridgman.[269] It was found for all specimens, except one containing 30 per cent nickel, that the effect of pressure could be reproduced by a second-degree formula of the form

$$\Delta R/R = ap + bp^2$$

TABLE 65.—THE TEMPERATURE COEFFICIENT OF

Composition, per cent		Temperature coefficient of electric resistance × 10³ per °C., at							
Ni	C	0°C.	50°C.	100°C.	150°C.	200°C.	250°C.	300°C.	350°C.
0	0	5.90	4.90	4.20	3.80	3.60	3.30	3.15	2.95
5.5	0.03	2.10	2.00	1.95	1.90	1.85	1.80	1.80	1.85
									1.80
9.5	0.12	1.65	1.65	1.70	1.80	1.95	2.00	2.00	2.00
		1.80	1.80	1.80	1.75	1.75	1.75	1.70	
9.55	0.59	2.75	3.00	3.40	2.85	1.75	1.40	1.25	....
		1.75	1.60	1.45	1.85	1.30	1.25	1.30	1.30
14.7	0.06	1.60	1.85	2.15	2.90	4.90	5.75	0.90	0.70
		1.70	1.80	1.85	1.90	1.80	1.70	1.60	1.50
19.2	0.03	2.80	4.10	6.80	1.00	0.75	0.63	0.57	0.54
		1.95	1.90	1.80	1.65	1.55	1.50	1.45	1.45
24.5	0.16	1.40	0.90	0.75	0.65	0.60	0.55	0.51	0.48
		1.60	1.60	1.60	1.55	1.55	1.40	1.40	1.35
25.0	0.07	4.80	3.20	0.95	0.79	0.68	0.59	0.52	0.47
		1.75	1.75	1.70	1.60	1.55	1.45	1.40	1.35
27.7	0.31	0.73	0.70	0.66	0.62	0.58	0.54	0.49	0.44
		1.50	1.45	1.45	1.40	1.35	1.26	1.20	1.20
29.15	0.18	0.78	0.70	0.63	0.59	0.55	0.51	0.47	0.44
		1.80	1.80	1.75	1.60	1.50	1.45	1.45	1.55
29.9	0.18	0.73	0.67	0.61	0.56	0.52	0.48	0.43	0.40
		1.50	1.45	1.35	1.20	1.00	0.95	0.92	0.86
35.2	0.13	1.80	1.50	1.25	0.95	0.67	0.57	0.49	0.42
44.6	0.04	3.35	2.95	2.60	2.20	1.85	1.45	1.10	0.85
50.3	0.05	2.70	2.40	2.40	2.25	2.05	1.80	1.55	1.40
56.5	0.06	2.95	2.75	2.50	2.35	2.20	2.00	1.90	1.72
65.0	0.03	2.80	2.85	2.90	2.70	2.65	2.40	2.10	1.95
73.8	0.01	3.70	3.50	3.10	2.95	2.70	2.45	2.20	2.15
85.35	0.03	3.75	3.45	3.15	2.85	2.60	2.45	2.35	2.25
98.17	0.06	4.30	3.70	3.40	3.25	3.20	3.15	3.40	2.55

* Ribbeck.[241]

where a and b are constants and p is pressure in kilograms per square centimeter. The constants are reproduced in Table 66. Data on the 30 per cent nickel alloy are given in Table 67.

155. Effect of Heat Treatment on Electric Resistance.—In general, the resistance of a given iron-nickel alloy is least for the fully annealed condition. According to data quoted by Bridgman,[269] the maximum difference appears in the 50 to 70 per cent nickel range and amounts to about 5 microhm-cm. for hard-drawn as compared with annealed wire.

The influence of cold work followed by thermal treatment on the electric resistivity of iron-nickel alloys is shown by measurements of Dahl.[556] The alloys were prepared from shot nickel and charcoal iron, plus 0.5 per cent manganese, and contained 30 to 100 per cent nickel. They were drawn to wire, annealed, then subjected to various treatments. Electric resistivity was determined for quenched specimens and (1) after cold drawing 95 per cent; (2) after annealing at 900°C. (1650°F.), then cold drawing 95 per cent; and (3) after annealing at 900°C., then holding at 420°C. (790°F.) for 40 hr. to obtain the state stable at ordinary temperature. Results, in comparison with values

ELECTRIC RESISTANCE OF IRON-NICKEL ALLOYS*

Temperature coefficient of electric resistance $\times 10^3$ per °C., at

400°C.	450°C.	500°C.	550°C.	600°C.	650°C.	700°C.	750°C.	800°C.	850°C.	900°C.	950°C.	1000°C.
2.80	2.65	2.50	2.35	2.20	2.10	2.15	2.75	0.93	0.60	0.43	0.30	0.25
1.85	1.90	2.00	2.31	5.10	0.90	0.45	0.35	0.30	0.29	0.29	0.25	0.22
1.75	1.70	1.70	1.65	1.60	2.00	2.60	1.80					
3.25	5.40	0.61	0.45	0.42	0.41	0.40	0.39	0.37	0.34	0.30	0.28	0.26
1.60	1.50	1.45	1.50	1.60	2.30	3.60						
0.97	0.70	0.58	0.50	0.44	0.39	0.35	0.33	0.31	0.29	0.27	0.26	0.26
1.35	1.35	1.30	1.40	1.70	7.90	0.40						
0.57	0.50	0.47	0.46	0.44	0.40	0.36	0.31	0.28	0.26	0.25	0.24	0.23
1.45	1.50	1.75	2.05	2.50	0.65							
0.52	0.50	0.48	0.42	0.38	0.35	0.31	0.30	0.30	0.29	0.29	0.28	0.28
1.45	1.40	1.45	2.00	0.76								
0.45	0.41	0.37	0.34	0.31	0.29	0.27	0.24	0.22	0.19	0.17	0.16	0.15
1.35	1.30	1.45	5.30									
0.42	0.39	0.36	0.33	0.30	0.29	0.28	0.26	0.24	0.22	0.20	0.19	0.18
1.45	1.85	2.00	4.50	0.72								
0.39	0.37	0.34	0.35	0.33	0.29	0.26	0.25	0.23	0.22	0.22	0.21	0.21
1.25	1.70	3.30										
0.42	0.39	0.36	0.34	0.32	0.29	0.26	0.24	0.23	0.21	0.20	0.18	0.16
1.65	1.90	2.15	0.40									
0.38	0.36	0.34	0.30	0.26	0.24	0.23	0.22	0.22	0.21	0.21	0.20	0.20
0.80	2.70	0.89										
0.37	0.33	0.30	0.27	0.25	0.23	0.21	0.20	0.20	0.19	0.19	0.18	0.18
0.59	0.41	0.28	0.24	0.22	0.22	0.22	0.21	0.20	0.20	0.20	0.19	0.19
1.25	0.94	0.47	0.30	0.25	0.20	0.17	0.17	0.16	0.16	0.15	0.15	0.15
1.60	1.35	1.10	0.70	0.20	0.18	0.17	0.17	0.17	0.17	0.16	0.16	0.16
1.85	1.70	1.65	1.75	0.60	0.28	0.17	0.17	0.17	0.17	0.17	0.16	0.16
2.10	2.10	2.20	2.35	0.50	0.26	0.21	0.20	0.20	0.19	0.19	0.18	0.18
2.30	2.65	1.90	0.95	0.62	0.52	0.44	0.41	0.39	0.38	0.38	0.37	0.37
1.15	0.90	0.83	0.80	0.77	0.74	0.72	0.69	0.65	0.62	0.59	0.57	0.55

TABLE 66.—THE EFFECT OF PRESSURE UP TO 12,000 KG. PER SQ. CM. ON ELECTRIC RESISTANCE OF IRON-NICKEL ALLOYS*

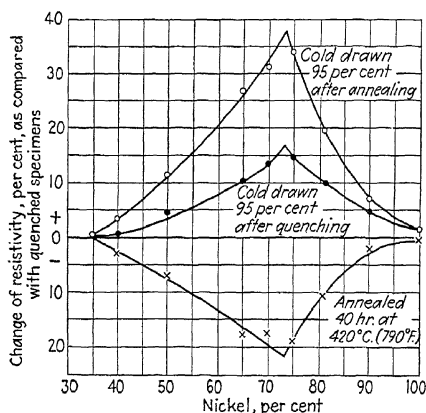| Nickel, per cent | $\Delta R/R = ap + bp^2$, p in kg. per sq. cm. | | | | | |
| | At 30°C. | | | At 75°C. | | |
	$a \times 10^6$	$b \times 10^{11}$	Deviation, per cent	$a \times 10^6$	$b \times 10^{11}$	Deviation, per cent
0	−2.427	+1.14	...	−2.450	+1.00	
10	+0.036	−8.0	5.1	−0.091	−3.00	2.9
25	+2.822	−0.92	0.2	+2.315	−0.92	1.9
40	+9.100	−6.06	0.1	+6.910	−7.08	0
50	+5.904	+5.62	0.2	+5.422	+3.68	0.3
60	+3.002	+2.29	0.9	+2.886	+1.70	
65	+1.930	+1.09	0.2	+1.776	+1.39	0.4
75	+0.456	......	2.0	+0.394	......	3.1
78.5	−0.129	......	6.2	−0.181	......	12.2
81	−0.389	......	3.3	−0.461	......	4.2
100	−1.905	+0.50	...	−1.925	+0.56	

* Bridgman.[269]

TABLE 67.—EFFECT OF PRESSURE ON ELECTRIC RESISTANCE OF A 30 PER
CENT NICKEL IRON-NICKEL ALLOY*

Pressure, kg. per sq. cm.	$\Delta R/R$ at 30°C.	$\Delta R/R$ at 75°C.
3,000	0.02478	0.02114
6,000	0.05078	0.04279
9,000	0.07751	0.06473
12,000	0.10477	0.08696

* Bridgman.[269]

for quenched specimens, are given in Fig. 255. It is to be seen
that the limiting compositions (nickel and the 30 per cent nickel
alloy) were unaffected by heat treatment. For the intermediate
alloys, annealing effected a marked reduction of resistivity,
whereas cold work appreciably increased the resistivity. The
maximum effect, according to Dahl's data, appears in the vicinity

FIG. 255.—Effect of heat treatment on the electric resistivity of iron-nickel
alloys.   (Dahl.[556])

of 73 per cent nickel; its significance is discussed elsewhere.
Other data and discussion were given by Dahl[409] in an earlier
article, Dahl and Pfaffenberger,[444,479] and Gumlich, Steinhaus,
Kussmann, and Scharnow,[276] among others. Most such
investigations, however, have been concerned primarily with
the study of the constitution of magnetically interesting alloys.

Heat treatment has a marked effect on the resistance of iron-nickel-carbon alloys capable of undergoing alpha-gamma transformation, as may be seen from Table 68, given by Portevin.[167] The large number of possible states of such alloys precludes generalization.

TABLE 68.—EFFECT OF HEAT TREATMENT ON ELECTRIC RESISTIVITY OF IRON-NICKEL-CARBON ALLOYS*

Composition, per cent		Resistivity, microhm-cm.	
C	Ni	Annealed at 1000°C. (1830°F.), cooled in 4 to 5 hr.	Annealed at 1300°C. (2370°F.), cooled in 3 days
0.35	9.7	30.7	36.1
0.4	12.2	36.0	40.4
0.3	15.0	49.0	69.7
0.5	11.7	45.7	55.3
0.6	7.0	30.6	42.9
0.75	7.0	31.0	44.5
0.8	7.1	33.6	44.9
0.8	9.9	40.0	55.9

* Portevin.[167]

156. Magneto-resistance and Mechano-resistance.—All metallic substances undergo change of electric resistance when subjected to a magnetic field. Ferromagnetic substances increase in resistance if the current and the magnetic field are parallel and decrease if they are perpendicular. Further, in ferromagnetic substances, the effect ordinarily attains its largest value in fields of less than 1000 oersteds, whereas non-ferromagnetic substances require fields of high strength. Closely connected with the magneto-resistance effect is the mechano-resistance effect. In general, the resistance of a ferromagnetic substance is more sensitive to non-isotropic stress and less simply related to intensity of stress than that of non-ferromagnetic substances.

Until several years ago, there was relatively little information on these effects in iron-nickel alloys; an exhaustive search of the literature by McKeehan[354] yielded only that given in Table 69. Considerable information, obtained in two laboratories, was

reported by McKeehan who chose, incidentally, the change of resistivity rather than proportional change of resistance. The data, in the form of numerous curves, are not reproduced here; further, their accompanying text does not lend itself to abridgment, consequently reference to the original article is recommended.

Other investigators of magneto- and mechano-resistance are Englert,[410] who stated that "with increasing tensile stress

TABLE 69.—LONGITUDINAL MAGNETO-RESISTANCE OF IRON-NICKEL ALLOYS*

Investigator and year	Composition, per cent			Tension, lb. per sq. in.	Maximum field strength, oersteds	Field strength for $(\Delta R/R)_{max.}$, oersteds	$(\Delta R/R)_{max.}$, per cent
	Ni	Cr	Mn				
Williams,[55] 1903.	47†	....	...	......	580	500	0.31
	47‡	....	...	......	740	405	0.028
	27	....	...	......	800	80	0.0045
	26	....	...	......	...	...	0.0018
	47	....	...	26,300	630	300	0.16
				32,500	770	300	0.13
Williams,[55] 1905.	24	....	...	......	800	300	0.06
	27.9	....	...	......	800	300	0.005
	35.5	....	...	......	800	300	0.08
	40	....	...	......	800	300	0.14
	44	....	...	......	800	300	0.155
	48.7	....	...	......	800	300	0.23
	57	....	...	......	800	350	0.46
	70	....	...	......	800	350	0.72
Obata,[165] 1921...	72.9	....	7	......	20,000	...	−0.059§
	56.3	15.6	3.2	......	1,300	600	0.035
	58.3	15.2	2.6	......	1,200	500	0.056

* McKeehan.[354]
† Unannealed.
‡ Annealed.
§ According to McKeehan, probably in error; since this alloy is ferromagnetic, it should show a positive value for $\Delta R/R$.

diminishing increase of electric resistance was observed in a longitudinal field and progressing decrease of resistance in a transverse field," Tammann and Caglioti,[471] Tammann and Rocha,[472] who investigated the effect of cold work and of recovery therefrom, and Guillet and Ballay,[187] who also investigated the effect of cold work.

According to McKeehan,[354] the close relationship of the magneto- and mechano-resistance effects was noted by H. D. Arnold, who expressed this equivalence by

$$\Delta R = f(H + kT)$$

where H is field strength, T is tension, and k is a constant. McKeehan himself concluded that the equivalence is not so perfect as the equation suggests.   A somewhat different approach
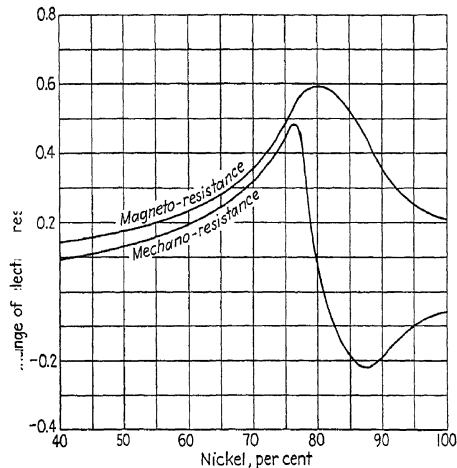

Fig. 256.—Semi-quantitative curves showing the variation with composition of the magneto- and mechano-resistance of iron-nickel alloys.   They are based on data given by McKeehan.[354]

was made by Schulze,[466] who concluded that the dependence of resistance upon magnetization can be expressed by

$$\Delta R/R = C(I^2 - I_0^2)$$

where I is intensity of magnetization and C is a constant. I_0 depends upon the internal strain of the substance.

All of the aforementioned investigators made use of iron-nickel alloys, but it seems out of place here to repeat detailed results; furthermore, the only clear-cut findings seem to be that electric resistance is definitely affected by magnetization and by mechanical stress and that there is an indifferent point for stress in the vicinity of 81 per cent nickel.   The direction of the

effects is indicated by the semi-quantitative curves of Fig. 256. The construction of these curves was guided by curves given by McKeehan.[354]

B. ELECTRIC PROPERTIES OF COMPLEX ALLOYS

Of considerable practical importance are the electric properties of complex alloys containing iron and nickel. Members of this group are used frequently for electric heating.
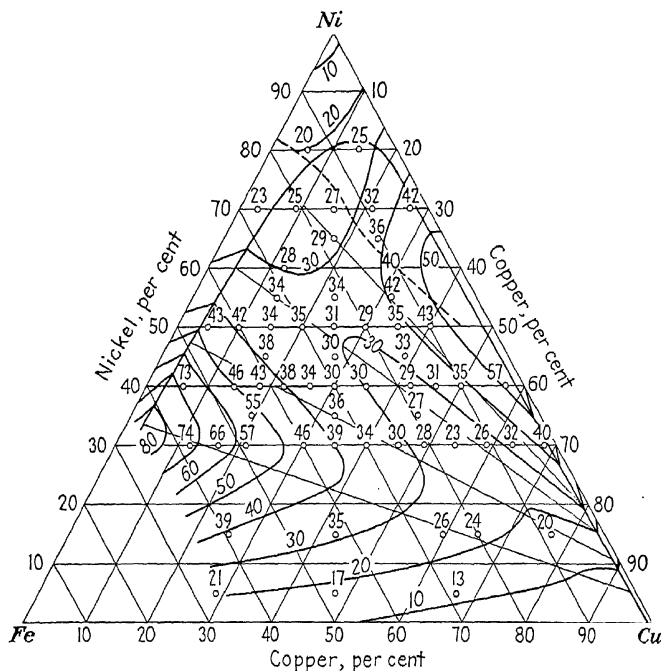

FIG. 257.—The electric resistivity (20°C.) of iron-nickel-copper alloys. (*Köster and Dannöhl.*[533])

The chapter closes with a review of data on thermal electromotive force. Much of this information is of little interest today.

157. Electric Properties of Iron-nickel-copper Alloys.—The resistivity of iron-nickel-copper alloys is fairly well known, mainly because of the measurements of Kosting[350] and of Köster and Dannöhl.[533]   Figure 257 shows the results of the latter for

20°C. Sections for elevated temperatures are not reproduced here.

The effect of thermal and mechanical treatments on the resistivity of these alloys was investigated by Dahl and Pfaffenberger[444,479] and by Kersten.[494] The alloys consisted mainly of those prepared from a 40 per cent nickel iron-nickel alloy by the addition of copper. Their "anomalous" behavior is of more concern from the point of view of magnetic properties, consequently is discussed elsewhere.

Much of the existing information on electric properties of complex iron-nickel-copper alloys is in the patent literature, which is not reviewed here. A few data from other sources, however, are assembled in Table 70.

TABLE 70.—ELECTRIC RESISTIVITY AT ROOM TEMPERATURE OF SOME COMPLEX IRON-NICKEL-COPPER ALLOYS

Investigator	Composition, per cent				Electric resistivity, microhm-cm.
	Fe	Ni	Cu	Other elements	
Anon.[373]...	17	76	5	2Cr	45
Anon.[207]...	17	76	5	2Cr	20 to 46
Courtois[334]	26	60	12	2Mn	171
Ballay[331]..	67	30	0.22	1Mn; 2Cr	

158. Electric Properties of Iron-nickel-cobalt Alloys.—The resistivity of this system has been well surveyed by Elmen,[297] whose results are shown in Fig. 258, and by Kühlewein,[352] who reported his results as curves of constant resistivity at room temperature. Where comparable, the two sets of results are in good agreement.

The only investigation of the effect of heat treatment on resistivity was conducted by Dahl[409] who determined the effect of tempering a quenched alloy containing 45 per cent nickel, 25 per cent cobalt, remainder iron. A tempering temperature in the immediate vicinity of 500°C. (930°F.) seemed to be most effective in removing the effect of quenching.

The resistivity of iron-nickel-cobalt alloys is increased markedly by the addition of such elements as titanium and molybdenum. For example, Elmen[527] found that the resistivity of an

alloy containing 45 per cent nickel, 25 per cent cobalt, remainder iron was increased from 18 to 80 microhm-cm. by the addition of 7 per cent molybdenum.

159. Electric Properties of Alloys Containing Chromium or Molybdenum.—The electric resistivity of alloys containing 78.5
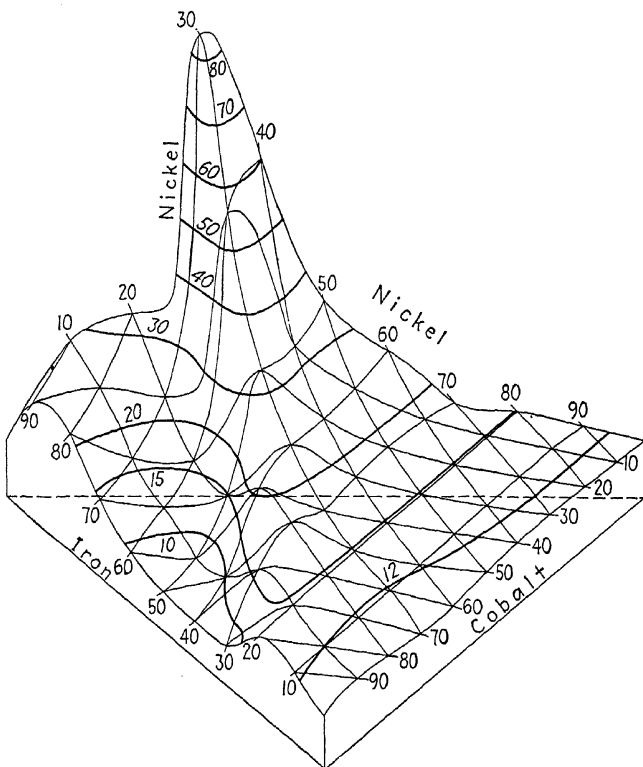

Fig. 258.—The electric resistivity (20°C.) of annealed iron-nickel-cobalt alloys. (*Elmen.*[297])

per cent nickel and chromium or molybdenum, determined by Elmen,[527] is given in Fig. 259. Such additions are important in magnetic materials (page 246) because of the resulting substantial increase of resistivity.

The electric resistivity of reversible iron-nickel-chromium alloys, as determined by Chevenard,[270] is given by Fig. 260.

Data on the whole system were reported by Dean[335] as lines of constant resistivity projected upon the concentration triangle. These lines, constructed from relatively few points, seem to be

Fig. 259.—The effect of chromium or molybdenum on the electric resistivity (20°C.) of a 78.5 per cent nickel iron-nickel alloy. (*Elmen.*[527])
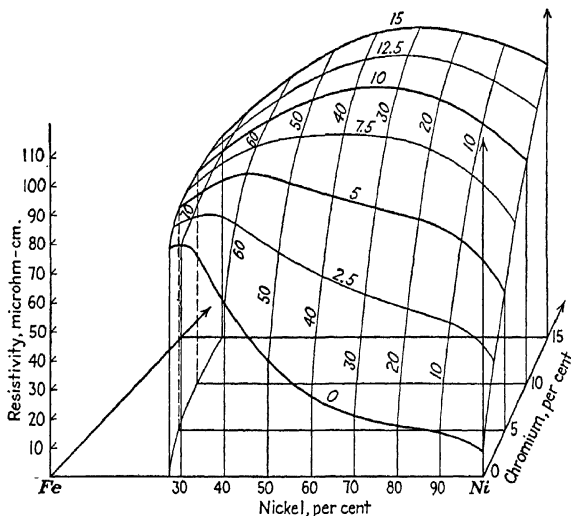

Fig. 260.—The electric resistivity (20°C.) of iron-nickel-chromium alloys. (*Chevenard.*[270])

in agreement with isolated values collected in Table 71. Information on the variation of resistivity with temperature of some iron-nickel-chromium alloys was given graphically by Chevenard.[270,271] According to Ballay,[331] an alloy containing 53.58

per cent nickel and 31.35 per cent chromium increased in resistivity from 114 to 125 microhm-cm. as the temperature was increased from 20 to 1000°C.

Mean temperature coefficients (20 to 100°C.) for iron-nickel-chromium alloys were given by Dean.[335] The smallest values—about 0.0001 per °C.—were found for alloys containing about 55 per cent nickel and 20 per cent chromium. Pressure coefficients for alloys containing 64 per cent nickel and 11 per cent chromium, and 30 per cent nickel and 2 per cent chromium, were respectively (approximately) 0.4×10^{-6} and 0.2×10^{-5}.

Iron-nickel-chromium alloys of the "nichrome" type are sufficiently important to merit separate discussion.

160. High-resistance Iron-nickel-chromium Alloys.—A well-known type of high-resistance alloy used for electric heating contains substantial percentages of iron and nickel. The composition and electric resistivity of typical alloys, given by Hunter

TABLE 71.—ELECTRIC RESISTIVITY OF SOME IRON-NICKEL-CHROMIUM ALLOYS

Investigator	Composition, per cent			Electric resistivity, microhm-cm. at 20°C.
	Fe	Ni	Cr	
Fischer[337]...............	78.3	5	16.6	85
	74	10	15.8	74
Klein[202]................	75	7	18	70
	26	62	12	100
Grossmann[339]...........	74	8	18	73
Ballay[331]...............	65	30	5	96
	13.77	53.58	31.35	114
	15	64	11	109
Goerens[197]...............	30	60	10	105
Schulze[508]...............	15 to 20	60 to 65	15 to 19	110 ±
Rohn[265]................	10	65	25	110
	10	70	20	108
Powell[578]...............	73.49	8.04	17.87	68*

* 74.3 microhm-cm. at 100°C., 95 at 400°C., and 114 at 800°C.

and Jones,[199] are assembled in Table 72. In general, the alloys used for electric heating are composed of nickel and chromium, or iron, nickel, and chromium, sometimes with addition of manganese or copper. For convenience, Hunter and Jones divided them into three groups:

A. Those suitable for operation below 500°C. (930°F.).

B. Those suitable for operation above 500°C. (930°F.).

C. Those high-resistance alloys having special properties for apparatus operating at room temperature.

The alloys of group *A* consist chiefly of nickel, but nickel has low resistivity at room temperature, although its resistance to oxidation at elevated temperature is greater than that of the common metals. The low resistivity of nickel can be increased by adding metals soluble in it. Such an alloy is typified by that given in the first row of Table 72. This alloy is especially susceptible to heat treatment. A specimen slowly cooled after annealing has much lower resistivity and a higher temperature coefficient than an unannealed wire; the values given are for slow cooling after heating to 1000°C. (1830°F.), and this treatment stabilizes the material for further cycles of heating and cooling. Small variations of impurity content have relatively large effect, consequently standardized production is sometimes difficult.

The second group, *B*, is composed essentially of iron, nickel, and chromium. These alloys have high resistivity and considerable resistance to oxidation at elevated temperature. From the standpoint of resistance to oxidation only, alloys low in iron content seem to be best. Of widest application because of its lower cost, however, is the alloy known as nichrome, which contains approximately 60 per cent nickel, 26 per cent iron, and 12 per cent chromium. It has higher resistivity than the low-iron alloy and a somewhat higher temperature coefficient. Resistivity and resistance to oxidation can be varied by modifying the composition.

The third group, *C*, ordinarily is composed of non-ferrous materials and, consequently, is not considered here.

161. Electric Properties of Iron-nickel-manganese Alloys.— The electric resistivity of iron-nickel alloys is increased by the addition of manganese. Values for alloys containing more than 50 per cent nickel and up to 15 per cent manganese for two conditions of heat treatment (quenched and tempered) were reported by Kussmann, Scharnow, and Steinhaus.[458] A valley of comparatively low resistance exists in the resistivity-concentration diagram between 70 and 80 per cent nickel for the tempered condition and in the vicinity of 10 per cent iron for the quenched

TABLE 72.—ELECTRIC RESISTIVITY OF IRON-NICKEL-CHROMIUM ALLOYS (CONTAINING ABOUT 0.2 PER CENT CARBON) OF THE NICHROME TYPE*

Composition, per cent				Electric resistivity, microhm-cm., at										
Fe	Ni	Cr	Mn	20°C.	100°C.	200°C.	300°C.	400°C.	500°C.	600°C.	700°C.	800°C.	900°C.	1000°C.
28.86	69.33	.....	1.30	20.6	28.8	39.8	52.3	66.0	81.6	98.5	101.8	104.2	107.0	109.8
67†	30	2	1	88	96	105	114	120	125	130	132	135	140	
28.70	59.29	10.75	1.54	105.2	.....	.....	115	117	118.5	119	120	121	122.5	124.4
27.86	59.02	10.90	1.54	106.3	.....	.....	115.5	117.4	119	119.6	120.5	121.3	122.6	124.6
26.97	59.57	11.05	1.69	114.5	.....	.....	125	127	128.8	129.3	129.8	130.7	132.1	134.1
24.97	61.75	11.45	1.19	110.5	.....	.....	118.4	120.2	121.7	122.3	122.8	123.5	124.9	126.9
24.35	62.00	11.70	1.46	108.6	.....	.....	116.5	118.4	120	120.4	121.1	122.1	123.5	125
24.88	61.20	12.05	1.44	110.1	.....	.....	117.2	119	120.2	120.7	121.4	122.5	124	125.7
10.53	69.35	17.95	1.58	113.5	.....	.....	117.8	119.2	120.5	120	120	120.1	120.9	121.6
13.77	53.58	31.35	0.0	114	.....	.....	119.5	121	122.5	122.6	123	123.5	124.3	125.2
48.45	27.62	21.10	0.85	103.3	.....	.....	115.6	119.1	122.1	124.8	126.7	128.8	130.8	132.5

* Hunter and Jones.[199]
† Nominal.

condition. In an earlier publication, Gumlich, Steinhaus, Kussmann, and Scharnow[341] noted a strong effect of thermal treatment on the resistivity of iron-nickel-manganese alloys. A few data from other sources are collected in Table 73.

Further information on the effect of heat treatment was supplied by Dahl,[409] who determined the effect of tempering on quenched alloys prepared from a 74 per cent nickel alloy by the addition of up to 12 per cent manganese. Reduced resistivity resulted from tempering in the 300 to 600°C. (570 to 1110°F.) region with the greatest effect in the vicinity of 500°C. (930°F.). The greatest reduction—more than 30 per cent—was observed for the 6 per cent manganese alloy. Data for a range of compositions (up to 15 per cent manganese) were given by Kussmann, Scharnow, and Steinhaus.[458] The maximum change of resistivity (about 55 per cent) upon tempering took place in alloys containing about 76 per cent nickel and 12 per cent manganese.

TABLE 73.—ELECTRIC RESISTIVITY OF SOME IRON-NICKEL-MANGANESE ALLOYS

Investigator	Composition, per cent			Resistivity, microhm-cm., at 20°C.
	Fe	Ni	Mn	
Hunter and Sebast[132]............	0*	100*	10*	28
	50	50	10	94.7
	100	0	10	46.8
	0	100	15	41.6
	50	50	15	98.3
	100	0	15	58
	0	100	20	51.2
	50	50	20	117
	100	0	20	61
Ballay[331].......................	74	25	1	83
		50	0.75	42.8
Anon.[373].......................	45	45	10	97
	49	50	1	50
	25	65	10	58
Gumlich, Steinhaus, Kussmann, and Scharnow[276]..............	42	50	8	82
	15.5	79	5.5	38
	9	80	11	46.5

* Hunter and Sebast's compositions are parts by weight.

According to Romanov,[396] alloys containing 0.2 to 0.3 per cent carbon, 40 to 50 per cent iron, 30 to 45 per cent nickel, and about 15 per cent manganese have a resistivity in the neighborhood of 80 to 90 microhm-cm. at room temperature and are characterized by small temperature coefficients. Hensel[382] found that alloys containing 14 to 15 per cent nickel, 10 per cent manganese, and 3.25 to 4.5 per cent titanium had resistivities close to 90 microhm-cm., whether quenched or quenched and tempered.

162. Electric Properties of Other Complex Alloys.—There is no doubt that the resistivity of iron-nickel-silicon alloys has been investigated, but the results have not found their way into any but the patent literature, consequently all that can be stated here is that the resistivity of iron-nickel alloys is increased by the addition of silicon. The influence of tempering on quenched alloys was investigated by Dahl[409] and by Dahl and Pfaffenberger,[444] using alloys prepared from a 74 per cent nickel iron-nickel alloy by the addition of up to 5 per cent silicon. Up to 2 per cent silicon, the effect of certain tempering temperatures was to reduce resistivity (as compared with the quenched specimens). The effect was most marked at about 450°C. (840°F.), less so at 600°C. (1110°F.); but still higher tempering temperatures increased resistivity over the initial values. The effect became less marked as silicon content approached 2 per cent. The behavior of the 3 and 5 per cent silicon alloys was the opposite; *i.e.*, an increase of resistivity was followed by a decrease.

Other additions, such as beryllium, for the purpose of precipitation hardening of iron-nickel alloys, have resulted in incidental observations on electric resistivity (as for following the course of precipitation). In this category are the contributions of Preisach[506] and of Dahl,[556] which may be consulted for complete information. For similar information on iron-nickel-aluminum and iron-nickel-titanium alloys, see Dahl and Pfaffenberger.[479]

The resistivity of iron-nickel-vanadium alloys was investigated in some detail by Kühlewein.[499] His constant-resistivity curves indicate that the addition of 10 per cent vanadium to reversible iron-nickel alloys increases their resistivity to well over 100 microhm-cm.

163. Thermal Electromotive Force.—Use is made of the phenomenon of thermal electromotive force in temperature-measur-

ing devices. Iron-nickel alloys, however, are unsuitable for thermocouple materials because of the irregularity of their curves for electromotive force versus temperature. Despite this fact, the phenomenon has received considerable attention. The first investigation of magnitude was that of Steinmann[36] in which alloys containing up to 44 per cent nickel were tested against lead. No simple relationship was found between nickel content and thermal electromotive force. This was followed by one by Belloc,[40] whose findings, in the main, confirmed those of

TABLE 74.—THERMAL ELECTROMOTIVE FORCE OF IRON-CARBON-NICKEL ALLOYS AGAINST IRON*

Cold-junction Temperature, 11°C.

Composition, per cent		Thermal electromotive force, millivolts, at		
C	Ni	75°C.	120°C.	225°C.
0.07	2.25	−0.468	−0.811	−1.626
0.12	5.23	−1.034	−1.810	−3.530
0.12	7.13	−1.327	−2.320	−4.418
0.13	10.10	−1.715	−2.920	−5.623
0.11	15.17	−2.264	−3.890	−7.361
0.18	20.49	−2.715	−4.611	−8.645
0.16	25.85	−2.391	−4.084	−7.306
0.12	30.00	−1.019	−1.676	−2.782
0.21	1.97	−0.475	−0.857	−1.563
0.20	4.20	−0.992	−1.642	−3.308
0.23	7.59	−1.267	−2.213	−4.227
0.21	9.79	−1.645	−2.797	−5.385
0.22	12.29	−1.857	−3.237	−5.969
0.23	15.04	−2.046	−3.580	−6.603
0.23	20.01	−2.127	−3.611	−6.835
0.23	25.06	−1.092	−1.861	−3.191
0.19	27.87	−0.995	−1.676	−2.658
0.80	2.20	−0.567	−0.988	−1.808
0.78	4.90	−1.028	−1.783	−3.294
0.81	7.09	−1.257	−2.170	−4.134
1.05	9.79	−1.476	−2.570	−4.692
0.76	12.27	−1.492	−2.638	−4.700
0.80	15.04	−1.491	−2.631	−4.766
0.80	20.01	−1.324	−2.197	−3.862
0.79	25.06	−1.153	−1.721	−2.911
0.81	29.96	−1.008	−1.661	−2.692

* Galibourg.[213]

TABLE 75.—THERMAL ELECTROMOTIVE FORCE OF SOME IRON-NICKEL
ALLOYS AGAINST COPPER*
Cold-junction Temperature, 0°C.

Composition, per cent					Thermal electromotive force, millivolts, at 100°C.
Ni	Cr	Mn	Si	C	
0	.....	.....	.....	.....	+0.86
17	.....	.....	.....	.....	−0.64
20	.....	.....	.....	.....	−0.55
30	.....	.....	.....	.....	−0.52
33.5†	.....	.....	0.16	0.25	−0.48
81.2†	.....	.....	0.014	0.19	−2.45
93	.....	.....	.....	.....	−1.90
94.6†	.....	.....	0.64	0.11	−1.40
96.3†	.....	.....	0.35	0.12	−2.00
100	.....	.....	.....	.....	−2.38
17	4	.....	.....	.....	−0.12
20	10	.....	.....	.....	−0.46
55	10	.....	.....	.....	0.0
60	15	.....	.....	.....	+0.07
55	20	.....	.....	.....	+0.07
55	25	.....	.....	.....	−0.08
77.5†	7	.....	0.03	0.22	+0.20
70.6†	13.1	.....	0.02	0.17	+0.20
70.6†	13.1	.....	0.02	0.20	+0.17
57.7†	31.9	0.20	0.30	0.40	−0.08
69†	22.7	0.30	0.25	0.20	+0.24
84†	11	.....	0.40	0.034	+1.49
81†	13.6	0.30	0.17	.....	+1.00
89.6	5.65	.....	.....	.....	+1.70
80.4†	15.6	.....	0.58	0.23	+0.76
89.7†	5.6	0.25	0.40	0.18	+1.51
10	.....	3	.....	.....	−1.09
12	.....	2	.....	.....	−1.02
17	.....	2	.....	.....	−1.50
17	.....	3	.....	.....	−0.79
17.5	.....	6	.....	.....	−0.73
22	.....	2	.....	.....	−1.84
44	.....	6	.....	.....	−0.59
58.3†	0.31	6.6	1	0.16	−0.94
82.8†	0.11	12	0.058	0.068	−1.11
88.5†	0.11	6.2	0.061	0.065	−1.60

* Fuller.[117]
† By analysis.

Steinmann. An extensive investigation on iron-nickel-carbon alloys against lead was conducted by Dupuy and Portevin.[100,116] Values for seemingly the same alloys, reported later by Galibourg,[213] are quoted in Table 74. Data obtained by Fuller[117] on iron-nickel, iron-nickel-chromium, and iron-nickel-manganese alloys against copper are given in Table 75. Other measurements on iron-nickel-chromium alloys against iron, made by Hunter and Bacon,[138] are reproduced in Table 76.

Data on several nickel steels, containing up to 7 per cent nickel, were given by Galibourg[176] in support of his suggestion that thermal electromotive force could be used as an analytic device. Further information on this device was furnished by Cazaud[333] who outlined possible errors and necessary precautions.

TABLE 76.—THERMAL ELECTROMOTIVE FORCE OF IRON-NICKEL-CHROMIUM ALLOYS AGAINST IRON*

Cold-junction Temperature, 20°C.

Composition, parts			Thermal electromotive force, millivolts, at								
Fe	Ni	Cr	138°C.	300°C.	305°C.	445°C.	518°C.	637°C.	646°C.	829°C.	830°C.
75	25	0	....	.....	8.50	13.69	......	......	14.48	......	14.57
75	25	10	....	.....	2.97	3.02	......	......	2.74	......	2.83
75	25	15	....	.....	2.98	3.00	......	......	2.78	......	2.94
75	25	20	....	.....	2.70	2.79	......	......	2.49	......	2.61
75	25	25	....	.....	2.73	2.68	......	......	2.16	......	2.14
50	50	0	6.25	11.45	....	.....	12.54	11.05	.....	10.46	
50	50	10	1.43	2.11	....	.....	1.14	0.16	.....	−0.54	
50	50	15	1.37	2.18	....	.....	1.68	1.09	.....	0.86	
50	50	20	1.22	1.81	....	.....	1.04	0.26	.....	−0.27	
50	50	25	1.29	2.00	....	.....	1.46	0.76	.....	0.33	
25	75	10	0.87	0.78	....	.....	−1.28	−2.99	.....	−4.90	
25	75	15	0.80	0.63	....	.....	−1.23	−2.81	.....	−4.47	
25	75	20	0.86	0.88	....	.....	−0.68	−1.95	.....	−3.28	
25	75	25	0.91	1.02	....	.....	−0.36	−1.57	.....	−2.77	

* Hunter and Bacon.[138]

Other investigations of the thermal electromotive force of iron-nickel alloys include: iron-nickel alloys against lead, −80 to 100°C., by Broniewski and Smolinski;[443] a 66 per cent nickel iron-nickel alloy against nickel, by Dannecker;[105] iron-nickel alloys against nickel-aluminum, nickel-chromium, and iron-nickel alloys, by Kowalke;[106] iron-nickel alloys against copper, by Ingersoll *et al.*,[152] Ballay,[331] Pepe,[166] and Majo;[194] iron-

nickel alloys against platinum, by Chevenard;[407] 60 per cent nickel iron-nickel-carbon alloys against nickel, by Hoffmann and Schulze;[150] iron-nickel-carbon alloys against iron-nickel-carbon alloys, by Campbell;[127] iron-nickel-copper alloys against copper, by Kosting;[350] and iron-nickel-chromium alloys against platinum, by Chevenard.[271] On the more complex effects, there is comparatively little information: MacLean[33] made a thermocouple of two wires containing 16.5 per cent nickel, one as received and the other stressed to fracture, and Smith and Dillinger[325] found a parallelism between length change and thermal electromotive force under the combined action of tension and longitudinal magnetic field. Pettorino[314] determined the effect of transverse magnetization on the thermal electromotive force of alloys containing 36 and 49 per cent nickel.

C. AUTHOR'S SUMMARY

1. The electric resistivity at 20°C. of irreversible iron-nickel alloys, *i.e.*, alpha-phase alloys, increases from about 9.6 microhm-cm. for iron to about 27 microhm-cm. at 10 per cent nickel. No definite statement can be made for alloys containing 10 to about 30 per cent nickel; because of varying degrees of completeness of the gamma-alpha transformation. The behavior of reversible alloys, *i.e.*, gamma-phase alloys, is unusual in that the curve is convex downward over most of its course. Available data appear to fall into two groups. The difference may be caused by difference of purity.

2. Nickel seems to reduce the temperature coefficient of electric resistivity of irreversible alloys; reasonable values seem to be 0.0065 per °C. for iron and 0.002 per °C. for the 10 per cent nickel alloy. Temperature coefficients of reversible alloys also fall into two groups. The only suggestion offered is again that difference of purity may be responsible.

3. It has been found that the effect of hydrostatic pressure on the electric resistance of iron-nickel alloys can be reproduced satisfactorily by a formula of the form

$$\Delta R/R = ap + bp^2$$

where p is pressure and a and b are constants.

4. Mechanical and thermal treatments have marked effect on the resistivity of gamma-phase iron-nickel alloys. The change

seems to be greatest in the neighborhood of 70 per cent nickel. The cause of the change is not yet understood fully.

5. The only definite statement made on effects such as magneto-resistance and mechano-resistance is that the electric resistance of iron-nickel alloys is changed by the application of a magnetic field and of mechanical strain. The direction of the effects is indicated by Fig. 256, page 353. If stress produces the same strain as magnetostriction, the magneto-resistance change (increase) is less. If stress produces strain opposite to that of magnetostriction, the magneto-resistance change is greater under stress.

6. The electric resistance of the ternary systems iron-nickel-copper, iron-nickel-cobalt, iron-nickel-chromium, and iron-nickel-manganese is fairly well known. There is in addition some information on quaternary alloys based on the foregoing systems.

7. An important alloy for electric heating contains roughly 60 per cent nickel, 26 per cent iron, and 12 per cent chromium.

8. Information on some complex alloys is restricted to patent literature. This is true of much of that existing on iron-nickel-silicon alloys, for example. Still other data have been obtained incidentally, as in following the course of precipitation hardening. This accounts for the few data on iron-nickel-beryllium, iron-nickel-aluminum, and iron-nickel-titanium alloys.

9. There is considerable information on the thermal electromotive force of iron-nickel alloys, even though they are not suitable thermocouple materials. Likewise, many data have been reported on complex alloys containing iron and nickel, but they are chiefly of academic interest.

MECHANICAL PROPERTIES OF IRON-NICKEL ALLOYS

*Effect of Nickel on Mechanical Properties of Iron—Effect of Heat
Treatment or Cold Working on Mechanical Properties of Iron-nickel
Alloys—Effect of Carbon on Mechanical Properties of Iron-nickel Alloys
—Effect of Temperature on Mechanical Properties—Author's Summary*

Credit for the first published report on the effect of nickel on
the mechanical properties of carbon steel must go to James
Riley[11] whose classic paper before the British Iron and Steel
Institute in 1889 stimulated world-wide research on alloys of
iron and nickel, and of iron, nickel, carbon, and other elements.
Although two of Stodart and Faraday's[2] alloys made around
1820 contained nickel (0.75 and 2.19 per cent), they were not
analyzed and their tensile properties were not determined until
some 110 years later (Hadfield[330]). The crude tests made by
Stodart and Faraday did not show that nickel steels had any
interesting possibilities.

Riley did not discover that nickel could be alloyed readily with
iron or with carbon steel or that it improved the properties to a
marked degree; in fact, as brought out in the discussion of Riley's
paper, work on these materials had been going on in France and
England for some time and patents had been issued more than a
year earlier to Marbeau in France and to Hall in England.
That nickel steel had been investigated with some completeness
in France is shown by the fact that James Kitson, in his presi-
dential address to the British Iron and Steel Institute in 1889,
just before Riley's paper was presented, exhibited test pieces
cut from French armor plate containing 5 per cent nickel.
Kitson reported that investigation of this material had shown a
tensile strength of 200,000 lb. per sq. in. with an elongation of
8 per cent.

Riley's paper on nickel steel was, however, the first detailed
report ever presented and without doubt was the most important
single factor in the development of the large variety of nickel-

containing industrial materials used today, materials ranging from the low-nickel and nickel-alloy structural and engineering steels and cast irons, through the nickel-alloy corrosion- and heat-resisting materials, to the binary and complex iron-nickel alloys which are non-magnetic, which have controlled expansion characteristics, and which have high magnetic permeability.

Within 10 years after Riley published his report the high-nickel alloys were used industrially. According to Colby,[48] one of the pioneers in the investigation of nickel steel in the United States, boiler tubes of 25 per cent nickel steel were used abroad in 1898, and 5 years later were tried by the United States Navy.

A. EFFECT OF NICKEL ON MECHANICAL PROPERTIES OF IRON

Nearly all the work on the effect of nickel on the tensile properties of iron was done in the 20 years immediately following the publication of Riley's paper, when interest in the use of nickel as an alloying element, especially for armor plate and ordnance, was at fever heat. Moreover, all this pioneer work was done before the nature of the irreversible alloys was clearly understood, consequently the erratic results obtained on alloys containing between 10 and 25 per cent nickel, especially after annealing, were the cause of much discussion. However, as the alloys in this composition range were hard and relatively brittle even after annealing, and promised nothing of commercial importance, at least so far as could be determined from the tensile properties, interest in them lagged quickly. Consequently, little work has been done on these alloys in the past 25 years.

164. Relation between Constitution and Tensile Properties.— Nickel is soluble in alpha iron; these solid solutions, in common with most solid solutions, are stronger than the original ferrite. Alloys containing 30 to 40 per cent nickel are predominantly austenitic and when annealed or quenched exhibit the usual properties of such materials, low yield and elastic ratios and high elongation and reduction of area.

Alloys containing approximately 10 to 25 per cent nickel are the so-called irreversible alloys. As these are cooled, phase changes continue to occur at temperatures as low as liquid air,

but when the alloys are reheated the changes are not reversible. These alloys are said to "freeze in" at about 500°C. (930°F.) and, as brought out in Chapter II, diffusion at temperatures below this becomes negligible, and equilibrium is either impossible or very difficult to attain. During the gamma-alpha transformation and while the alloys are cooling from a high temperature, various amounts of a martensite-like constituent are formed, depending upon composition, cooling rate, and other factors. This constituent resembles martensite not only in its appearance under the microscope, but also in that it is responsible for high strength values and correspondingly low values for elongation and reduction of area. From this it follows, of course, that the tensile properties of iron-nickel alloys of a composition within the range of irreversibility depend almost wholly upon the amount of this martensitic constituent; this in turn depends principally upon the treatments to which the alloys are subjected at a high temperature and in cooling before testing.

The sluggishness of transformation in the iron-nickel alloys is modified by the presence of carbon. In general, carbon shifts to lower nickel percentages the concentration range where the martensitic constituent is formed. In addition, as discussed in Chapter III, nickel is a graphitizing element. According to the constitutional diagram for nickel steel and cast iron, published elsewhere,[584] in low-nickel alloys graphite forms when the carbon is about 1.25 per cent; in high-nickel alloys this carbon concentration is reduced to somewhat less than 1 per cent. As this constitutional diagram is more directly applicable to the commercial nickel steels and cast irons, it receives detailed attention in the second volume of this monograph.

Some of the early investigators, particularly Dumas[50] and Carpenter, Hadfield, and Longmuir,[59] suspecting peculiarities in the alloys containing 15 to 25 per cent nickel, determined mechanical properties after cooling their specimens to low temperatures, in some cases as low as the temperature of liquid air—about −190°C. (−310°F.)—and holding at these temperatures for various lengths of time. Under certain conditions the martensitic constituent forms at these low temperatures but, as the amount formed depends upon the time at temperature and the carbon content and as the alloys cannot attain equilibrium by such treatment, the results reported are erratic.

The mechanical properties of iron-nickel and iron-nickel-carbon alloys containing about 8 to 25 per cent nickel depend, therefore, chiefly upon the amount of hard, brittle martensitic constituent formed, complicated in the case of the latter alloys by the effect of carbon when present in amounts greater than about 0.75 per cent in high-nickel alloys and about 1.25 per cent in low-nickel alloys. As it is practically impossible to attain equilibrium in these alloys at atmospheric temperature, and as the amount of the martensite depends upon the prior treatment, the reported mechanical properties of these alloys are, in general, valid only for those particular specimens upon which the values were obtained.

165. General Effects of Small Amounts of Nickel on Mechanical Properties of Iron.—For at least 40 years it has been well known that small amounts of nickel when added to iron or to iron containing low carbon (less than 0.20 per cent) increase tensile strength, yield strength, yield ratio, and impact resistance. Elongation is lowered but reduction of area is affected little if any. As long ago as 1899, Browne[30] worked out a relationship for hot-worked and heat-treated alloys of varying carbon content. A number of other investigators, notably Abbott,[115,125] Gebert,[136] the metallurgical staff of the National Bureau of Standards,[183] and, recently, Maurer and Korschan,[460] have also determined the effect of nickel on the mechanical properties of alloys and of steels in analogous structural conditions.

By correlating all these data it may be concluded that: 1 per cent nickel increases the tensile strength about 4000 lb. per sq. in.; for annealed alloys of negligible carbon, it increases the yield strength about 5000 lb. per sq. in., and for alloys of 0.20 to 0.30 per cent carbon, about 6000 lb. per sq. in. Elongation is reduced some 3 to 5 units, and reduction of area is mostly unaffected. The resistance of the material to impact is greatly increased by nickel.

A comprehensive investigation by Maurer and Korschan[460] on the transverse properties of large forgings containing approximately 0.20 per cent carbon showed that 2 per cent nickel increased the tensile strength 30 per cent, the yield strength 60 per cent, with an insignificant change in values for elongation and reduction of area. The effect of this amount of nickel on impact resistance was notable—77 per cent increase.

Specific data on the effect of nickel on annealed steel containing 0.30 per cent carbon, recently published,[584] show the following:

Nickel, per cent	Tensile strength, lb. per sq. in.	Yield strength, lb. per sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness number
0	70,000	40,000	26	50	145
3.50	90,000	60,000	27	55	175
5.00	95,000	65,000	28	56	185

Summing up, it may be stated that nickel up to 8 or 10 per cent, when added to iron or to iron containing low carbon, and when the alloys have been similarly heat treated, increases the tensile and yield strengths and yield ratio, it has no effect or at most a slightly unfavorable unit effect on ductility as represented by elongation and reduction of area, and it increases greatly the impact resistance. For alloys treated so that the tensile strengths are the same, low percentages of nickel increase yield strength, elongation, and reduction of area. In addition, McAdam[192] has shown that nickel increases the endurance ratio, apparently by strengthening the ferrite.

The beneficial effects of nickel when added to cast iron or to steel containing up to 0.50 per cent carbon will be more apparent when the data in the second volume of this monograph are examined in detail. It is also shown there that nickel minimizes aging effects in low-carbon steel and greatly reduces impact brittleness caused by aging.

166. Tensile Properties of Hot-worked Iron-nickel Alloys.— The tensile properties of hot-worked or hot-worked and normalized (air-cooled) iron-nickel alloys based upon the work of nine investigators* are shown in Fig. 261. With the exception of a single value by McKnight[281] for a very low carbon, 2 per cent nickel steel, the values by the Bureau of Standards,[183] most of which were obtained by analyzing and correlating previous work, and those by Pilling and Brophy, all the data upon which Fig. 261 is based, were obtained more than 25 years ago.

* Riley,[11] Hadfield,[31] Dumas,[41,50] Guillet,[56] Giesen,[73] Burgess and Aston,[80] McWilliam and Barnes,[96] National Bureau of Standards,[183] McKnight.[281]

Because of the age of most of the work on the tensile properties of iron-nickel alloys and because of the uncertainty of composition of the alloys used by these early investigators Pilling and Brophy* determined, especially for this monograph, mechanical properties of seven alloys made from ingot iron and high-purity
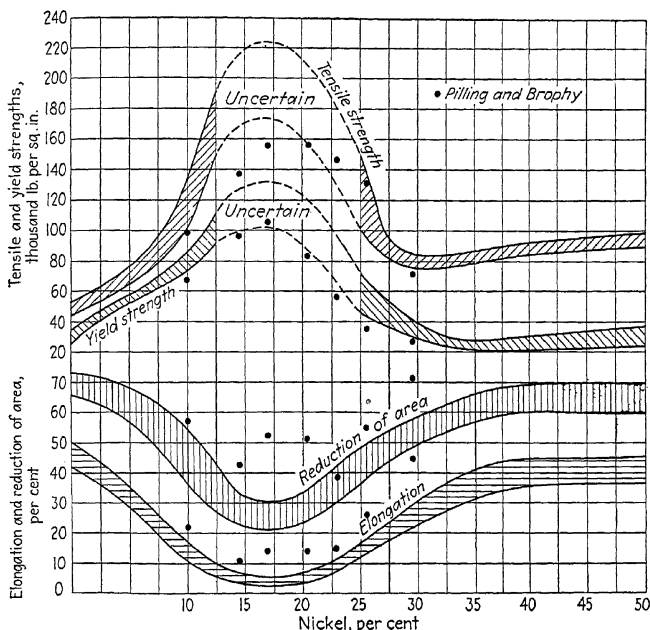

FIG. 261.—Approximate tensile properties of *hot-worked* iron-nickel alloys containing 0.05 to 0.20 per cent carbon. Alloys containing 0.12 to 0.20 per cent carbon usually have tensile- and yield-strength values near the upper limit and elongation and reduction-of-area values near the lower limit of the ranges shown. Based on data of the investigators enumerated in the footnote on page 372.

nickel and containing 10, 14, 17, 20, 23, 26, and 29 per cent nickel. Their results are discussed in sections 168 and 174 and are shown as plotting points in Figs. 261, 262, and 264.

In correlating the older data for Fig. 261 the values available were divided into two groups, one containing less than 0.12 per cent carbon, the other containing 0.12 to 0.20 per cent carbon. In general, the values for the higher carbon group fall near the

* See footnote, p. 13.

upper limit of the tensile- and yield-strength range and near the lower limit of the elongation and reduction-of-area range.

Because air cooling from the hot-working temperature or from a high normalizing temperature is sufficiently rapid to produce in small sections a fairly constant amount of the martensitic constituent for any alloy in the composition range 10 to 25 per cent nickel, the values obtained by the nine investigators were fairly constant (at least for iron-nickel alloys of this composition), varying less than 40,000 lb. per sq. in. in tensile and yield strengths, and less than 5 per cent in elongation. Reduction-of-area values, especially for alloys containing 15 to 30 per cent nickel, were very erratic, possibly owing as much to imperfect testing methods and unsound test bars as to the nature of the alloys themselves.

As shown in Fig. 261, the addition of up to 10 per cent nickel to iron raises the tensile and yield strengths, the latter more than the former. Elongation is lowered by nickel from an average of about 38 per cent to about 10 per cent; reduction of area is affected slightly. The structural change and the accompanying changes in mechanical properties of iron-nickel alloys are not abrupt. This is clearly shown in Fig. 261. Some of the strengthening effect of the martensitic constituent is apparent in the hot-rolled alloys with a nickel content as low as 8 or 9 per cent, while (as is evident from the properties) the duplex constituent has not entirely disappeared until the nickel content is more than 30 per cent.

Pilling and Brophy's results were obtained on melts made from iron and nickel of relatively high purity (see page 378 for analysis) and contained 0.04 to 0.06 per cent carbon. Considering the conditions under which these alloys were made and tested, the values shown by plotting points in Fig. 261 should be the most accurate. The tensile- and yield-strength values fall near or below the lower line of the hatched areas, while the values for elongation and reduction of area are in general higher than the older data. Pilling and Brophy's reduction-of-area data for the 10 to 23 per cent nickel alloys indicate that, owing to the martensitic structure, the values in this composition range are likely to be erratic.

The austenitic alloys (30 to 50 per cent nickel) show slightly increasing tensile strength and slightly decreasing ductility with increasing nickel.

167. Tensile Properties of Annealed Iron-nickel Alloys.—The correlated tensile properties of annealed iron-nickel alloys containing less than 0.20 per cent carbon, shown in Fig. 262, are based on the work of 15 investigators.* Nearly all the data used

FIG. 262.—Approximate tensile properties of *annealed* iron-nickel alloys containing 0.05 to 0.20 per cent carbon. Alloys containing 0.12 to 0.20 per cent carbon usually have tensile- and yield-strength values near the upper limit and elongation and reduction-of-area values near the lower limit of the ranges shown. Based on data of the investigators enumerated in the footnote on this page.

were reported more than 25 years ago. The recent data of Pilling and Brophy are shown as plotting points.

In the irreversible alloys, when annealed, the structural uncertainty and the accompanying wide variation in tensile properties become very pronounced, so much so that even a range of tensile and yield strengths could not be plotted for alloys containing

*Hopkinson,[10] LeChatelier,[14] Rudeloff,[29] Hadfield,[31,62] Osmond (in discussion of Hadfield's[31] paper), Dumas,[41] Butler,[45] Colby,[48] Portevin,[76] Révillon,[77] Burgess and Aston,[80] McWilliam and Barnes,[96] Guillet,[162] MacPherran,[163] National Bureau of Standards.[183]

12.5 to 25 per cent nickel.   An alloy containing 10 per cent nickel showed a spread in the reported tensile results of about 35,000 lb. per sq. in.

Despite widely varying values for tensile and yield strengths, the results reported by the 15 investigators indicate consistently that the alloys containing 10 to about 25 per cent nickel are relatively brittle and that the maximum brittleness* as shown by elongation and reduction of area occurred in alloys containing 15 to 20 per cent nickel.

As was the case with Pilling and Brophy's data on hot-worked alloys (Fig. 261), their values for tensile and yield strengths are lower and their values for elongation and reduction of area are higher than those of the older investigators.   In the composition range of 14 to 23 per cent nickel, reduction-of-area values are likely to be erratic.

With full realization that there is slight justification for such a procedure, the maximum and minimum values plotted in Figs. 261 and 262 have been averaged.   The resulting values for each 5 per cent nickel have been assembled in Table 77.   This compilation makes several things clear.   First and most important, annealing reduces the yield strength of the alloys containing gamma phase; this is especially evident in those alloys that are largely austenitic, that is, containing 30 per cent or more nickel. Further, it is probable that annealing has little effect on elongation and reduction of area, although it may be found when further work is done that it increases slightly the elongation of those alloys in which martensite is not the predominating structural constituent.

168. Pilling and Brophy's† Data on Hot-worked and Annealed Iron-nickel Alloys.—Seven small iron-nickel alloy heats were melted from high-purity nickel and ingot iron in a high-frequency induction furnace, and the ingots were forged into 1-in. octagon bars.   Standard specimens for tensile (0.505 in. round) and impact (0.394 in. square) tests were cut from these bars after the following treatments:

---

* Brittleness as used here is, of course, a relative term.   The martensitic iron-nickel alloys are brittle as compared with the ferritic or austenitic iron-nickel alloys.   If compared with a water-quenched and untempered high-carbon steel, these alloys show considerable ductility.

† See footnote, p. 13.

1. As forged.
2. Furnace cooled from 900°C. (1650°F.).
3. Water quenched from 900°C. (1650°F.).
4. Water quenched as in 3 and tempered at 400°C. (750°F.).

TABLE 77.—AVERAGE TENSILE PROPERTIES OF HOT-WORKED AND ANNEALED
IRON-NICKEL ALLOYS CONTAINING LESS THAN 0.20 PER CENT CARBON

Nickel, per cent	Hot rolled				Annealed			
	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation, per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation, per cent	Reduction of area, per cent
5	80,000	55,000	25	62	70,000	56,000	31	62
10	120,000	90,000	10	45	115,000	65,000	20	50
15	180,000	130,000	8	28	160,000	100,000	8	40
20	175,000	120,000	10	33	160,000	90,000	10	45
25	145,000	70,000	20	45	120,000	50,000	20	50
30	77,000	40,000	35	60	79,000	30,000	35	60
35	75,000	42,000	36	65	82,000	24,000	36	62
40	86,000	51,000	36	64	90,000	27,000	40	65
45	92,000	53,000	35	62	92,000	29,000	40	65
50	92,000	52,000	33	61	95,000	32,000	41	65

The analyses were selected so that the properties would fall in the range of greatest uncertainty of Figs. 261 and 262. The composition of the alloys and their properties as forged and annealed are given in Table 78 and as plotting points in Figs. 261 and 262.

The most marked variation from the older data, which has been mentioned earlier, is that, in general, the alloys tested by Pilling and Brophy had lower tensile and yield strengths and higher elongation and reduction of area than the values selected from earlier reports. The Pilling and Brophy data also confirm what was noted during the correlation of the older data; *viz.*, that alloys whose composition falls into the range where the maximum amount of martensite is present (13 to 23 per cent nickel) are likely to show erratic properties, especially marked in reduction of area.

The increasing amounts of austenite as the nickel increases from 20 to 29 per cent are clearly indicated (Table 78) by the

decreasing strength and hardness and by the increasing elonga-
tion, and especially by the higher impact values. Except for
the increase in the reduction-of-area values for the 10 to 20 per
cent nickel alloys the most pronounced effect of annealing is a
lowering of the yield strength and proportional limit, especially
of the latter. Annealing also lowered the tensile strength of
the 10 and 14 per cent nickel alloys.

Brophy and Miller* recently determined tensile-property data
of an annealed alloy containing 36 per cent nickel, using standard
0.505-in. specimens. The proportional limit was determined by
a Ewing extensometer. Their average results, together with
those reported by the Bureau of Standards[183] and by Mac-
Pherran,[163] are given in Table 79 together with average proper-
ties from Table 77 for comparison.

TABLE 78.—MECHANICAL PROPERTIES OF HOT-WORKED AND ANNEALED
IRON-NICKEL ALLOYS*

Alloy No.	Composition, per cent		Tensile strength. lb./sq.	Yield strength, lb./sq.	Proportional limit, lb./sq.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact, ft-lb.	Brinell hardness
	Mn	Ni							
				Hot worked					
T12233	0.05	0 35	0.10 9.98	119,400	89,000	41,800	7.0	21.7	44	287
12234	0.06	0 40	0.10 13.96	152,900	110,500	41,800	10.0	36.0	34	327
12235	0.05	0 36	0.10 16.94	149,900	111,000	40,500	10.5	36.3	22	321
11433	0.06	0.34	0.12 20.48	157,900	88,100	39,100	10.5	25.8	28	339
11434	0.05	0 35	0.09 23.00	153,800	67,800	38,800	13.0	37.2	30	311
11435	0.04	0 28	0.08 25.91	127,200	44,200	20,000	25.5	52.5	70	217
11436	0.04	0.34	0.09 29.11	70,300	45,500	28,000	39.0	70.1		126
				Annealed					
T12233	0.05	0.35	0.10 9.98	98,500	63,000	22,500	23.3	59.6	61	212
12234	0.06	0 40	0.10 13.96	138,500	94,500	24,800	11.0	43.4	42	313
12235	0.05	0 36	0.10 16.94	147,300	105,800	39,800	14.5	52.2	33	306
11433	0.06	0 34	0.12 20.48	153,800	81,300	33,900	15.5	50.5	28	326
11434	0.05	0.35	0.09 23.00	150,500	57,500	26,700	13.7	38.1	30	301
11435	0.04	0 28	0.08 25.91	128,200	34,200	20,500	26.2	54.0	90	206
11436	0.04	0 34	0.09 29.11	65,300	25,900	14,100	46.0	71.2	86	117

* Pilling and Brophy, unpublished data, Research Laboratory, The International Nickel
Company, Inc.

* See footnote, p. 13.

TABLE 79.—TENSILE PROPERTIES OF ANNEALED INVAR

Investigator	Composition, per cent			Anneal- ing tem- perature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Pro- por- tional limit, lb./sq. in.	Elon- gation in 2 in., per cent	Re- duc- tion of area, per cent
	C	Mn	Ni	°C.	°F.					
Brophy and Miller*...	Low	0.50	36	790†	1450	71,400	41,800	32,000	41	71.9
MacPherran[163]......	0.25	0.55	33.9	800	1475	85,000			43	
Bureau of Standards[183]	0 08	0.50	36	800	1475	72,500		24,000	39.2	67.5
From Table 77.	Low	0.50	35			82,000	24,000		36	62

* Unpublished data, Research Laboratory, The International Nickel Company, Inc.
† Followed by a stress-relieving anneal at 370°C. (700°F.).

Other properties reported by Brophy and Miller were

Modulus of elasticity, lb. per sq. in............. 20,500,000
Brinell hardness............................. 131

The yield strength and proportional limit were much higher than the value obtained at the Bureau of Standards and those given in Table 77, and the tensile strength was lower.

169. Effect of Nickel on the Hardness of Iron.—Hardness tests on hot-worked or annealed iron-nickel alloys containing less than 0.20 per cent carbon have been reported by Guillet,[56,162] Révillon,[77] Roush,[86] Maurer and Schmidt,[164] and, more recently, by Reed[428] and by Scheil and Tonn.[507] In addition, the metallurgical staff of the National Bureau of Standards critically examined the older data and gave values which they considered to be the best available. No correlation of early results is possible. As an example of the wide variation: Roush[86] reported a scleroscope value of 18 (equivalent to about 120 Brinell) on an annealed alloy containing 0.09 per cent carbon and 10 per cent nickel, while Reed[428] reported 262 Brinell on an alloy containing 0.11 per cent carbon and 10.36 per cent nickel. Values reported for a 15 per cent nickel alloy varied from 205 to 315 Brinell. The most that can be said for the early work is that it indicates that the addition of nickel increases the hardness of iron, and that the hardness of the irreversible alloys varies widely with their structural condition.

The Brinell hardness values reported by Scheil and Tonn[507] for annealed iron-nickel alloys containing up to 28 per cent nickel

and less than 0.05 per cent carbon and the values obtained by
Pilling and Brophy (see Table 78) are plotted in Fig. 263.   Values
of Maurer and Schmidt[164] (determined by a 5-mm. ball and a
750-kg. load) for alloys containing 0.07 per cent carbon or less
and those of Reed,[428] also for low-carbon alloys, are included
for comparison.   Figure 263 shows clearly how the hardness
increases with increasing amounts of martensite, and decreases
again with increasing austenite.   Considering the nature of the

FIG. 263.—Brinell hardness of annealed iron-nickel alloys.

martensitic alloys, the results by Scheil and Tonn and by Pilling
and Brophy check fairly well.

170. Effect of Nickel on Other Mechanical Properties.—The
pioneer investigation of iron-nickel and iron-nickel-carbon alloys
by Rudeloff[22,29] included compressive tests.   In the cast, rolled,
and rolled and annealed alloys containing 0.13 per cent or less
carbon, the addition of nickel increased the compressive strength
and reduced the percentage decrease in height of the cylinders
tested.   The increase in strength was uniform with increasing
nickel up to about 8 per cent and followed fairly closely the
curve of tensile strength (Figs. 261 and 262).   The one alloy in
the irreversible range tested, containing 15.6 per cent nickel, had
a very high strength and no ductility as measured by decrease

in height of the cylinder. In general, the shear strength followed the curve for compressive strength.

Compressive tests by Hadfield[31] on alloys containing 0.27 to 49.65 per cent nickel with carbon between 0.13 and 0.23 per cent confirmed the trend but not the values reported by Rudeloff. Hadfield found high strength and marked brittleness for alloys containing 11.39, 15.48, and 19.64 per cent nickel with carbon around 0.20 per cent. In shear tests made by Portevin[76] the same trend due to nickel was evident, with maximum shear strength in alloys containing 12 to 20 per cent nickel.

Few impact values for annealed low-carbon iron-nickel alloys, determined at normal temperature, have been reported. Tests by Guillet[56] and Chevenard[173] indicate that nickel lowers the impact as the percentage increases to about 10; the irreversible alloys have a relatively low impact resistance and the austenitic alloys are very ductile. The data of Pilling and Brophy (Table 78) indicate that, as compared with a heat-treated medium- or high-carbon steel, the martensitic alloys are relatively ductile. For none of the alloys containing between 10 and 29 per cent nickel was the Izod impact value lower than 22 ft-lb. Pilling and Brophy also determined V-notch Charpy impact values; these followed the same trend as the Izod values given in Table 78; the lowest Charpy impact resistance (30 to 36 ft-lb.) was found for the annealed 17 to 23 per cent nickel alloys; the highest values for the annealed material were 107 ft-lb. for the 26 per cent nickel alloy and 202 ft-lb. for the 29 per cent nickel alloy. The few published data on iron-nickel-carbon alloys indicate that carbon lowers the impact resistance of the ferritic alloys.

A number of investigations have been reported in which the impact resistance of iron-nickel alloys as dependent upon the temperature was determined. These are discussed in a later section of this chapter.

B. EFFECT OF HEAT TREATMENT OR COLD WORKING ON MECHANICAL PROPERTIES OF IRON-NICKEL ALLOYS

There have been relatively few investigations on the effect of heat treatment or cold working on the mechanical properties of iron-nickel alloys. This is to be expected; the ferritic alloys are of interest industrially only when there is enough carbon present so that the material can more properly be classed as a steel than

as a binary alloy. The duplex alloys do not respond to annealing and are, consequently, too hard for industrial fabrication, and the austenitic alloys are important chiefly for other properties such as expansion or magnetic characteristics, although some are used because of their strength at low temperatures, as in refrigerating equipment.

The effect of nickel on carbon steels is dealt with in detail in Volume II of this monograph; a few general conclusions regarding the effect of nickel in heat-treated carbon steels together with the available data on quenched or cold-worked iron-nickel alloys are given in the following pages.

171. General Effects of Small Amounts of Nickel on Mechanical Properties after Quenching.—Quenching iron-nickel alloys fixes at room temperature the structure existing at the temperature of treatment. The properties after quenching depend, therefore, upon the relative amounts of the alpha and gamma solid solutions which were present at the high temperature, provided that no carbon is present. No data are available for alloys that were essentially carbon free; practically all the data discussed hereafter show the effect of nickel on quenched iron-nickel alloys containing between 0.05 and 0.10 per cent carbon.

Small amounts of nickel when added to carbon steels containing less than 0.30 or 0.40 per cent carbon will, after heat treatment, increase ductility with no sacrifice in strength. In materials treated to the same tensile strength, nickel increases the yield ratio, elongation, reduction of area, and impact resistance, and the increase is more marked as the tensile strength increases. To show this effect, Table 80 has been prepared. The values for carbon steels were taken from charts given by French and Sands[483] and by Sisco;[612] the values for heat-treated nickel steels were taken from the former's report.

As the mechanical properties of a heat-treated steel depend upon many factors, the data given in Table 80 indicate only the *probable* values which will result *in most cases* when a carbon steel and a 3.5 per cent nickel steel are heat treated to the same tensile strength. In the case of carbon steels values were chosen which resulted from the heat treatment giving the best combination of properties.

172. Heat Treatment of Austenitic Iron-nickel Alloys.—In the usual sense, of changing the mechanical properties to a marked

degree, heat treatment has no effect on the austenitic iron-nickel alloys. Invar is sometimes annealed at 760 to 820°C. (1400 to 1500°F.) to relieve strains[431] and is occasionally quenched to produce special expansion properties.

Austenitic nickel steels do not harden by nitriding, if there is no element present, such as chromium or manganese, which will form a finely dispersed and insoluble nitride. Jones[453,491] found no increase in surface hardness upon nitriding a 34 per cent nickel steel, and a 26 per cent nickel, 13 per cent chromium, 3.5 per cent tungsten steel. A steel containing 15 per cent nickel and 5 per cent manganese, however, responded to the nitriding treatment.

TABLE 80.—EFFECT OF 3.5 PER CENT NICKEL ON MECHANICAL PROPERTIES OF IRON-CARBON ALLOYS HEAT TREATED TO A SPECIFIC TENSILE STRENGTH

Tensile strength, lb./sq. in.	Carbon steel				3.5 per cent nickel steel			
	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact value, ft-lb.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact value, ft-lb.
70,000	45,000	33	70	104	45,000	33	75	110
80,000	52,000	29	67	96	55,000	30	73	105
90,000	65,000	26	64	75	68,000	28	70	100
100,000	73,000	23	58	60	80,000	27	67	90
110,000	82,000	19	52	45	90,000	25	64	80
120,000	90,000	16	47	35	100,000	23	62	65
130,000	98,000	14	44	30	110,000	20	60	58
140,000	105,000	12	42	23	117,000	17	57	50

173. Properties of Quenched Iron-nickel Alloys.—Most of the early investigators who determined the properties of rolled, forged, or annealed iron-nickel alloys also determined the properties after quenching. Data by eight of these investigators* plus the results of Dahl and Pawleck[557] have been correlated and averaged. Results for the alloys containing less than 12

* Moulan,[18] Rudeloff,[22,29] Osmond (in discussion of Hadfield's[31] paper), Dumas,[41,50] Butler,[45] Guillet,[56,162] Révillon,[77] and National Bureau of Standards.[183]

per cent and more than 30 per cent nickel were consistent enough
so that probable values are shown by the dotted lines in Fig. 264.
Data for all of the properties of the seven alloys containing 10 to
29 per cent nickel specially prepared by Pilling and Brophy and
for tensile strength only of alloys containing 35 to 80 per cent

FIG. 264.—Probable tensile properties of quenched low-carbon iron-nickel
alloys (0.15 per cent or less carbon), based on data of the investigators enumer-
ated in the footnote on page 383.

nickel determined by Dahl[556] are also plotted. Values for
tensile and yield strengths of the 10 per cent nickel alloy tested
by Pilling and Brophy are considerably lower than the average
values of the older work.

As indicated by Fig. 264, the addition of nickel to iron con-
taining less than 0.10 per cent carbon increases the tensile and
yield strengths rapidly after quenching, and lowers the elongation

and reduction of area, the former more than the latter. As is the case with the hot-rolled and annealed material (see section 168) the martensitic alloys may have erratic properties, especially reduction of area (see the 20 and 23 per cent nickel alloys in Fig. 264).

At elevated temperature, alloys containing 25 to about 28 per cent nickel contain enough gamma phase so that, with certain carbon contents and quenching conditions, the formation of the martensitic constituent may be wholly prevented; an alloy containing as little as 25 per cent nickel may be completely austenitic and may have a tensile strength of about 80,000 lb. per sq. in. and relatively high ductility. On the other hand, under other quenching conditions, enough of the duplex constituent may be present so that the alloy may have a tensile strength of 160,000 lb. per sq. in. and the accompanying low values for elongation and reduction of area.

As the nickel increases, the probability of retaining austenite upon quenching increases, until with about 30 per cent or more nickel the alloys are austenitic under all quenching conditions. By averaging the values given in Fig. 262 for annealed alloys—a procedure of somewhat doubtful accuracy but which may be justified to show the trend—the results for annealed alloys and the values for quenched alloys may be compared, as in Table 81. This comparison indicates that the annealed alloys of this composition range have somewhat higher strength and lower elongation and reduction-of-area values than the corresponding quenched alloys.

The Brinell hardness values of the quenched alloys as reported in the older literature are very erratic. Recent results reported by Köster and Tonn[498] and by Scheil and Tonn[507] on high-purity alloys indicate that the addition of nickel increases the Brinell hardness number from about 100 for iron to about 260 for a 10 per cent iron-nickel alloy. For quenched material in the irreversible range these investigators do not agree on hardness values. Köster and Tonn reported a maximum Brinell number of 320 and Scheil and Tonn a maximum of 265 at about 12 per cent nickel; values by the former for alloys containing 15 to 25 per cent nickel are some 30 to 50 Brinell numbers higher than the values reported by Scheil and Tonn for alloys of corresponding composition.

TABLE 81.—APPROXIMATE TENSILE PROPERTIES OF ANNEALED AND QUENCHED IRON-NICKEL ALLOYS CONTAINING FROM 2 TO 50 PER CENT NICKEL

Nickel, per cent	Annealed				Quenched			
	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation, per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation, per cent	Reduction of area, per cent
2	60,000	42,000	40	68	88,000	50,000	37	66
4	66,000	50,000	33	64	140,000	90,000	26	63
6	72,000	57,000	28	60	150,000	110,000	18	58
8	95,000	62,000	23	55	150,000	118,000	14	48
10	115,000	65,000	20	50	152,000	123,000	12	43
12	160,000	80,000	16	45	154,000	124,000	12	43
16	165,000	100,000	8	40	156,000	120,000	10	44
20	160,000	90,000	10	45	154,000	90,000	12	46
25	120,000	50,000	20	50	130,000	33,000	20	55
30	79,000	30,000	35	60	66,000	25,000	45	70
35	82,000	24,000	36	62	68,000	26,000	46	72
40	90,000	27,000	40	65	74,000	27,000	47	73
45	92,000	29,000	40	65	80,000	29,000	48	72
50	95,000	32,000	41	65	82,000	30,000	48	70

Scheil and Tonn did not determine hardness on alloys containing more than 27 per cent nickel; values by Köster and Tonn indicate that the austenitic alloys have a Brinell hardness of 115 to 125.

The hardness values reported by Scheil and Tonn for annealed and for quenched alloys indicate that quenching shifts the peak of the hardness curve to lower nickel concentrations. The same phenomenon for tensile strength is shown in Figs. 262 and 264.

174. Pilling and Brophy's* Data on Heat-treated Iron-nickel Alloys.—The effect of water quenching and of water quenching followed by tempering on alloys containing 10 to 29 per cent nickel is shown in Table 82. The values for the quenched and untempered specimens are shown also as plotting points in Fig. 264.

* See footnote, p. 13.

If the data given in Table 82 are compared with those for the annealed alloys (Table 78), the following facts stand out: (1) Water quenching increases the tensile strength, yield strength, and proportional limit of the 10 per cent nickel alloy and lowers the elongation, reduction of area, and Izod impact values; the 14 per cent nickel alloy is similarly affected but much less drastically. (2) Water quenching has little effect on any of the mechanical properties of the other alloys if the high reduction-of-area value for the annealed 20 per cent nickel alloy is ignored. (3) Tempering the water-quenched specimens has a marked effect on most of the properties; the tensile strength of all the alloys is lowered and the proportional limit of the tempered specimens is greatly increased. The most notable effect of tempering is the decrease in tensile strength of the 20 and 23 per cent nickel alloys accompanied by an increase in hardness, and the great increase

TABLE 82.—MECHANICAL PROPERTIES OF HEAT-TREATED IRON-NICKEL
ALLOYS*

Alloy No.	Composition, per cent			Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Proportional limit, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact, ft-lb.	Brinell hardness
	C	Mn	Ni							
Water quenched from 900°C. (1650°F.)										
T12233	0.05	0.35	0.10	9.98	150,300	119,300	47,000	13.0	43.7	34	334
T12234	0.06	0.40	0.10	13.96	152,800	120,600	53,100	13.0	44.0	35	329
T12235	0.05	0.36	0.10	16.94	146,000	113,300	48,000	13.0	46.6	29	307
T11433	0.06	0.34	0.12	20.48	154,500	86,100	26,600	9.5	17.7	28.	326
T11434	0.05	0.35	0.09	23.00	149,500	56,700	22,200	13.5	33.5	30	306
T11435	0.04	0.28	0.08	25.91	127,500	28,300	18,300	24.5	56.0	62	234
T11436	0.04	0.34	0.09	29.11	65,300	21,900	13,900	48.0	71.3	85	113
Water quenched from 900°C. and tempered 1 hr. at 400°C. (750°F.)										
T12233	0.05	0.35	0.10	9.98	121,000	116,600	102,300	17.5	55.5	53	268
	0.06	0.40	0.10	13.96	126,000	122,200	106,100	17.5	61.6	53	279
T12235	0.05	0.36	0.10	16.94	119,500	114,200	79,000	10.0	44.9	44	274
T11433	0.06	0.34	0.12	20.48	120,800	114,700	96,900	21.2	61.2	48.5	368
T11434	0.05	0.35	0.09	23.00	108,300	99,000	65,800	23.5	67.0	55	317
T11435	0	04	0.28	0.08	25.91	100,300	55,200	25,000	33.2	63.8	87	171
T11436	0.04	0.34	0.09	29.11	63,800	24,800	16,800	44.5	70.9	86	120

* Pilling and Brophy, unpublished data, Research Laboratory, The International Nickel Company, Inc.

in yield strength of the higher nickel alloys and in proportional limit of all the alloys together with increase in elongation, reduction of area, and impact resistance.

175. Effect of Cold Work.—There are a few scattered data on the effect of cold work on the properties of iron-nickel alloys, too few, however, to indicate definitely the effect of either nickel or cold work. Much has been done, of course, on the cold rolling or cold drawing of nickel steels, hence it is possible to compare broadly the effect of cold work on the properties of a nickel and of a carbon steel of the same carbon content. Such data, reported by French and Sands,[433] calculated in percentage of the property of the material as hot rolled, are given in Table 83. These data indicate that for light drafts the 0.20 per cent carbon steel hardens more rapidly with the same reduction in cold drawing than the 0.15 or 0.20 per cent carbon, 3.5 per cent nickel steel.

TABLE 83.—EFFECT OF COLD WORKING ON MECHANICAL PROPERTIES OF HOT-ROLLED CARBON AND 3.5 PER CENT NICKEL STEELS*

Property	0.20 per cent carbon steel, cold drawn from $1\frac{1}{16}$- to $\frac{1}{2}$-in. rounds	3.5 per cent nickel steel, cold drawn from $1\frac{1}{16}$- to $\frac{5}{8}$-in. rounds	
		0.15 per cent carbon	0.20 per cent carbon
Tensile strength, lb. per sq. in., percentage increase	37	22	25
Yield strength, lb. per sq. in., percentage increase	94	59	75
Elongation in 2 in., per cent, percentage decrease	57	44	45
Reduction of area, per cent, percentage decrease	13	2	3
Brinell hardness, percentage increase	39	16	42

* Calculated from data reported by French and Sands.[433]

The only data available on the effect of cold working on the properties of austenitic alloys of variable nickel content were reported by Dahl.[556] In connection with tests on electric

resistivity, he determined tensile strength after cold working 95 per cent, preceded or followed by heat treatment. The resultant values are given in Table 84. The alloys were melted from shot nickel and Swedish iron and contained 0.5 per cent manganese. They were drawn to wire, annealed, and then treated as shown in Table 84.

Pawlek,[537] in connection with his studies on the effect of recrystallization temperature on magnetic properties, determined the effect of reheating on the tensile strength and elongation (in 100 mm.) of identical specimens of an iron-nickel alloy containing 40 per cent nickel, after cold working with 80 and 98.5 per cent reduction in cross-section. The trend of the values

TABLE 84.—TENSILE STRENGTH OF IRON-NICKEL ALLOYS, AS QUENCHED, COLD WORKED, AND HEAT TREATED, AND HEAT TREATED PLUS COLD WORKED*

Nickel, per cent	Tensile strength, lb. per sq. in.			
	Quenched from 900°C. (1650°F.)	Cold worked with 95 per cent reduction and tempered at 420°C. (790°F.)	Quenched from 900°C. (1650°F.) and cold worked with 95 per cent reduction	Tempered at 420°C. (790°F.) and cold worked with 95 per cent reduction
35	71,100	130,900	130,900	125,200
40	76,800	142,200	133,700	128,000
50	83,900	159,300	147,900	139,400
65	89,600	182,100	156,500	156,500
70	92,400	202,000	. . . . . .	165,000
75	93,900	219,000	. . . . . .	170,700
80	91,000	192,000	150,800	166,400
90	74,000	150,800	136,600	139,400
100	59,700	122,300	119,500	119,500

* Dahl.[556]

shown in Fig. 265 is self-explanatory and brings out clearly the difference in properties caused by the difference in degree of cold working and the fact that the recrystallization temperature is approximately 500°C. (930°F.). Noteworthy is the lowering of the elongation in the specimen cold worked with a 98.5 per cent reduction after reheating to 900°C. (1650°F.) or above. This does not occur in the specimen cold worked 80 per cent.

Dahl and Pawlek,[557] in continuing this work on magnetic properties, tested an iron-nickel alloy sheet containing 40 per cent nickel and determined, incidentally, the effect of fiber structure

FIG. 265.—Effect of reheating on the tensile strength and elongation of a cold-worked iron-nickel alloy containing 40 per cent nickel.   (*Pawlek*.[537])

on the tensile strength.   Their results may be summarized briefly as follows:

1. For specimens cold rolled with 80 per cent reduction, annealed at 1000°C. (1830°F.), and cold rolled with 50 per cent reduction, tensile strength was 90,000 to 94,000 lb. per sq. in., with a slightly lower strength at an angle of 90 deg. to the direction of rolling.

2. For specimens cold rolled with 50 per cent reduction, annealed at 1000°C. (1830°F.), and cold rolled with 94 per cent

reduction, tensile strength was 111,000 to 116,000 lb. per sq. in., with a slightly lower strength at an angle of 45 deg. to the direction of rolling.

3. For specimens cold rolled with 50 per cent reduction, annealed at 700°C. (1290°F.), and cold rolled with 98.5 per cent reduction, tensile strength was 57,000 to 70,000 lb. per sq. in., with the lowest values at an angle of 45 deg. to the direction of rolling.

4. For specimens cold rolled with 98.5 per cent reduction, annealed at 1000°C. (1830°F.), and cold rolled with 50 per cent reduction, tensile strength was 88,000 to 93,000 lb. per sq. in., with the lowest values at an angle of 60 deg. to the direction of rolling.

Results of an investigation to show the relation between location of the specimen in a cold-rolled and annealed sheet and the nickel content were reported by Wassermann.[583] The alloys contained 30, 40, and 60 per cent nickel and were made from ingot iron and carbonyl nickel. The sheets were cold rolled with a reduction of 95 per cent to 0.3 mm. (0.012 in.). They were then annealed at 1000°C. (1830°F.) to produce a uniform cubic texture. Specimens were cut at various angles to the original direction of cold rolling and the tensile strength and elongation were determined. The results are given in

TABLE 85.—EFFECT OF DIRECTION OF TEST SPECIMEN ON THE TENSILE PROPERTIES OF IRON-NICKEL ALLOYS COLD ROLLED AND ANNEALED TO PRODUCE CUBIC TEXTURE*

Angle between major axis of test piece and direction of rolling, deg.	30 per cent nickel		40 per cent nickel		60 per cent nickel	
	Tensile strength, lb./sq. in.	Elongation,† per cent	Tensile strength, lb./sq. in.	Elongation,† per cent	Tensile strength, lb./sq. in.	Elongation,† per cent
0	50,500	11	57,600	9	71,800	20
20	47,700	50	53,300	45	59,700	42
45	54,000	59	57,600	54	66,900	54
70	48,400	45	53,300	41	62,600	37
85	53,300	24	55,500	18	66,900	29
90	54,800	13	61,200	14	74,700	26

* Wassermann.[583]
† Gage length not given.

Table 85.   The properties, especially elongation, are markedly affected by the direction of the test piece.

C. EFFECT OF CARBON ON MECHANICAL PROPERTIES OF IRON-NICKEL ALLOYS

The mechanical properties of the commercial iron-carbon-nickel alloys, in other words the nickel steels, will receive detailed attention in Volume II of this monograph; it is only necessary, therefore, in this first volume on special alloys to consider very briefly the general effect of carbon when it is present in increasing amounts in iron-nickel alloys.   For convenience of discussion, the iron-nickel alloys are divided arbitrarily into those containing 5 to 20 per cent nickel and those containing 25 to 50 per cent nickel.   It will be recalled (see page 370) that, in general, carbon shifts to lower nickel percentages the concentration range where the duplex constituent is formed.   It will also be recalled that nickel is a graphitizing element; Rudeloff[22,29] found graphite by analysis in cast alloys containing 9 per cent nickel and 0.80 per cent carbon, and in alloys containing 60 per cent nickel with carbon as low as 0.50 per cent.   Graphite naturally has such an important effect on the properties that any tensile values reported for alloys containing graphite or even suspected of containing graphite are likely to be erratic.

176. Effect of Carbon on Tensile Properties of Alloys Containing 5 to 20 Per Cent Nickel.—Since Riley's[11] work, published in 1889, the tensile properties of alloys containing 5 to 50 per cent nickel and 0.05 to 1.0 per cent carbon have been the subject of at least 31 investigations.*   A few of these investigators made alloys of constant nickel and varying carbon contents; most of them, however, interested primarily in a material of a specific nickel content, made their alloys of relatively impure metals and determined the carbon as an impurity.   The available data were correlated, the clearly erroneous results weeded out, and the remainder weighted and averaged.   Results for alloys

---

* Riley,[11] Howard,[16] Moulan,[18] Rudeloff,[29] Hadfield,[31,62] Osmond and Arnold (in discussion of Hadfield's[31] paper), Dumas,[41,50] Butler,[45] Guillet,[56,162] Carpenter, Hadfield, and Longmuir,[59] Giesen,[73] Portevin,[76] Révillon,[77] Roush,[86] Bregowsky and Spring,[97] Froehlich,[111] Cohade,[142] Hatfield,[143,278] Remington and Dickenson,[154] MacPherran,[163] Welter,[171] Müller,[179] National Bureau of Standards,[183] French and Tucker,[186] Schoenmaker,[363] and Pilling and Worthington.[395]

containing 5 to 20 per cent nickel are plotted in Figs. 266 and 267.

In general, the trends brought out by Fig. 266 are as expected. In the predominantly ferritic alloys (5, 6, and 7 per cent nickel) increasing carbon content in the hot-worked, normalized, or annealed specimens is accompanied by an increase in tensile and yield strengths and by a decrease in elongation and reduction of area. With all carbon percentages, up to the maximum for which data are reported, annealing reduces slightly the tensile

Fig. 266.—Effect of carbon on the tensile properties of iron-nickel alloys containing 5 to 10 per cent nickel, based on data of the investigators enumerated in the footnote on page 392.

and yield strengths and increases the elongation and reduction of area.

In alloys containing 8 per cent nickel the changes due to small percentages of carbon are gradual; when 0.70 per cent carbon is present, however, enough of the second phase is present after annealing so that the alloy has high strength and very low elongation. In the 10 per cent nickel material there are apparently increasing amounts of the second phase present as the carbon increases.

Data for 15 per cent nickel alloys were available only for annealed specimens (Fig. 267). The maximum amount of duplex

constituent is apparently formed when the carbon is 0.25 to 0.30 per cent. With higher carbon percentages an increasing amount of austenite is formed, accompanied by a regular and marked decrease in tensile and yield strengths. All the alloys containing 15 per cent nickel are brittle as is apparent from the low values for elongation.

Alloys containing 20 per cent nickel and less than 0.10 per cent carbon have high strength and low elongation. Increasing

FIG. 267.—Effect of carbon on the tensile properties of iron-nickel alloys containing 12 to 20 per cent nickel, based on data of the investigators enumerated in the footnote on page 392.

amounts of austenite are formed, with strength decreasing as the carbon increases from 0.10 to 0.80 per cent.* All of them have low elongation values.

It is impossible to give any data on the effect of carbon on quenched iron-nickel alloys containing about 8 to 20 per cent nickel. All of the reported values are so erratic that, although the early investigators did not usually suspect the formation of quenching cracks, defective test pieces are indicated in nearly every instance.

* Although no graphite was shown by the analysis of the 0.80 per cent carbon alloy, it is possible that some was present.

177. Effect of Carbon on Tensile Properties of Alloys Containing 25 to 50 Per Cent Nickel.—The effect of carbon on hot-worked, normalized, or annealed iron-nickel alloys containing 25, 30, and 50 per cent nickel is shown in Fig. 268. There were sufficient values on the 25 per cent nickel alloy to indicate with fair certainty the trend in all properties except the elongation of the annealed specimens. Graphite, although not determined by the investigators, may have been present in some of the higher

Fig. 268.—Effect of carbon on the tensile properties of iron-nickel alloys containing 25 to 30 per cent nickel, based on data of the investigators enumerated in the footnote on page 392. .

carbon alloys; when its presence was suspected from the reported properties the values were not included in the averages from which the curves were drawn.

As Fig. 268 indicates, the maximum amount of the duplex constituent in either hot-worked (or normalized) or annealed 25 per cent nickel alloys was present in those containing 0.20 per cent carbon. Peculiarly, the high strength of the alloys containing 0.10 to about 0.30 per cent carbon is not accompanied by the usual low elongation and reduction-of-area values. Those containing more than 0.40 per cent carbon are predominantly

austenitic. That the tensile strength is somewhat higher than would be expected for austenitic alloys may be explained by the strengthening effect of carbon or by the presence of traces of the martensitic constituent. The former explanation is the more likely one, as a strengthening effect with increasing carbon is clearly evident in the 30 per cent nickel specimens (Fig. 268).

Despite the fact that invar (36 per cent nickel) is one of the most common of the austenitic iron-nickel alloys, there are few published data which show the effect of carbon on its properties. Values have been reported by Dumas[41] for the rolled and quenched condition, by Giesen[73] for "naturally hard" alloys, the National Bureau of Standards[183] for the rolled, annealed, and quenched, and by Hatfield[278] for the air-cooled condition. Giesen's results, the only ones on material containing more than 0.25 per cent carbon, are clearly out of line with what would be expected for austenitic alloys. It is possible that his specimens were rolled at temperatures where work hardening occurred.

Of the few values published, the results by the National Bureau of Standards seem to be the most reliable. The average values for the annealed and the quenched specimens, which checked closely, are as follows:

Property	0.05 per cent carbon	0.22 per cent carbon
Tensile strength, lb. per sq. in...	72,000	84,000
Yield strength, lb. per sq. in.....	23,000	27,000
Elongation in 2 in., per cent.....	36	40
Reduction of area, per cent......	63	66

From these results it is apparent that carbon increases tensile and yield strengths. The effect on elongation and reduction of area is slight; probably there is a slight increase in both properties.

D. EFFECT OF TEMPERATURE ON MECHANICAL PROPERTIES

There are surprisingly few data on the effect of small amounts of nickel on the mechanical properties of iron containing less than 0.05 per cent carbon, as a function of temperature. Some work has been done on the low- and elevated-temperature properties of the iron-nickel alloys containing more than 15 per

cent nickel, and an enormous volume of information is available on simple and complex nickel steels and other alloys containing nickel, when tested at other than room temperature.

Such data on the structural and engineering nickel steels are summarized and discussed in the second volume of this monograph; the available store of knowledge on the binary iron-nickel alloys is summarized in the present chapter, while the following chapter contains information on the properties of those ternary and more complex special alloys in which nickel is the predominating alloying element.

178. General Effects of Nickel on Mechanical Properties as a Function of Temperature.—The effect of temperature on the mechanical properties of high-purity iron and carbon steels has been summarized in previous monographs of the series,* where it is shown that anomalies in the properties occur in the blue-heat range, 250 to 300°C. (480 to 570°F.), or in the range of secondary brittleness, 450 to 600°C. (840 to 1110°F.). Little information exists from which it can be determined whether small amounts of nickel have any effect on these anomalies. Plotting MacPherran's[163] values for a steel containing 0.21 per cent carbon and 3.25 per cent nickel against results for an unalloyed 0.18 per cent carbon steel obtained by French and Tucker[186] indicates that the peak in tensile strength and the lowest values for elongation and reduction of area for the nickel steel occur at a temperature some 50 to 100°C. (90 to 180°F.) higher than for the plain carbon steel. As there are so many factors—for example grain size, method of determining temperature, speed of testing, and others—that affect the properties at elevated temperature, it is unsafe to draw any conclusions from this limited comparison.

Data reported by French and Sands[483] for low-carbon boiler plate indicate that a hot-rolled steel containing 0.19 per cent carbon, 0.67 per cent manganese, and 2.16 per cent nickel has a yield strength some 10,000 lb. per sq. in. higher at temperatures between 15 and 370°C. (60 and 700°F.) than steel containing 0.27 per cent carbon and 0.67 per cent manganese. The Charpy impact values of the nickel steel in this temperature range are 10 to 15 ft-lb. higher than the values for the carbon steel.

* "The Metal—Iron,"[520] Chaps. X and XI, and "The Alloys of Iron and Carbon,[612] Vol. II—Properties," Chaps. XII and XIII.

There seems to be little doubt that nickel, at least in iron-carbon alloys, improves the low-temperature ductility. As discussed in detail by Sisco,[612] it is a characteristic of carbon steels that they lose ductility (as measured by the single-blow impact test) rapidly and erratically at or slightly below room temperature. Probably much of the variation in low-temperature impact resistance of low- and medium-carbon steels of apparently the same composition is due to a difference in grain size. In this connection Sisco stated:

The work on the relation between low-temperature impact resistance and grain size has shown clearly that no definite conclusions on the effect of impurities or of small amounts of manganese, silicon, chromium, copper, and other elements (with the possible exception of nickel) can be formulated unless the grain-size variable is first taken into consideration. Although it is probable that carbon steels of small grain size have better low-temperature impact resistance than corresponding coarse-grained steels, a high degree of low-temperature toughness is apparently impossible to attain in carbon steels as a class; hence, in those applications where shock must be withstood at very low temperatures, alloy steels are usually specified.

The action of nickel in improving the low-temperature impact properties seems to be of threefold character: (1) Nickel steel has initially higher room-temperature impact resistance; (2) nickel apparently lowers the temperature where the rapid loss of ductility occurs; and (3) it apparently lowers the rate of loss of ductility in the brittle range. French and Sands[433] gave the following data:

Nickel, per cent	Charpy impact value, ft-lb., at	
	Room temperature	−45°C. (−50°F.)
0	80	7
1	94	30
2	88	35
3	88	40
4	75	50

The steels used contained 0.20 per cent carbon and were normalized. The impact specimens were 0.394 in. square with a 45-deg. V-notch, 0.079 in. deep and a bottom radius of 0.01 in.

After various heat treatments French and Sands found that at −45°C. (−50°F.) a 0.35 per cent carbon, 3.5 per cent nickel steel had a much higher impact resistance than a 0.35 per cent carbon steel similarly treated. The data are as follows:

Treatment	Charpy impact value, ft-lb., at			
	Room temperature	−45°C. (−50°F.)	Room temperature	−45°C. (−50°F.)
	Nickel steel		Carbon steel	
Water quenched and tempered at 540°C. (1000°F.)	96	100	80	20
Normalized............	56	25	36	6
Annealed..............	60	16	21	5

The favorable effects of nickel on low-temperature impact resistance are brought out in more detail in the discussion of nickel steels in Volume II of this monograph.

Austenitic nickel steels have high ductility at low temperatures; as shown in section 181, their impact resistance at −190°C. (−300°F.) is the same as at room temperature.

179. Effect of Temperature on Properties of Iron-nickel Alloys Containing Less than 15 Per Cent Nickel.—The only data available on the effect of temperature on the properties of iron-nickel alloys containing less than 15 per cent nickel are impact tests at elevated temperature reported in 1909 and 1910 by Guillet and Révillon[74,75,83] and the low-temperature investigation of the impact resistance of carbon and alloy steels by Yamada[248] in 1926, which included steels containing 0.27 per cent carbon and 7.2 per cent nickel. In giving reliable information these tests leave much to be desired.

Yamada made Charpy impact tests (round specimen, 45-deg. V-notch, 1.5 mm. deep) at temperatures between +15 and −190°C. (+60 and −310°F.) on a variety of carbon and alloy steels heat treated in different ways. For the annealed steels containing about 0.30 per cent carbon the effect of low temperatures on the resistance to impact is shown in Fig. 269. While the actual values obtained by Yamada may be criticized, all the

specimens were tested under the same conditions; hence Fig. 269 probably indicates with reasonable accuracy the relative toughness of these steels.   Three facts stand out: (1) At a temperature

FIG. 269.—Effect of low temperature on the impact value of annealed carbon and alloy steels containing 0.30 per cent carbon.   (*Yamada.*[248])

of −190°C. (−310°F.), all the steels had an impact resistance of less than 1 ft-lb.; (2) at temperatures between −20 and −100°C. (−5 and −150°F.), the steel containing 7 per cent nickel had a higher impact resistance than any of the others; and (3) under the

testing conditions used by Yamada the steels containing 3.0 and 4.5 per cent nickel did not have, when annealed, markedly better impact resistance at low temperatures than the other steels tested.

All the steels tested by Yamada had greatly improved resistance to impact at low temperatures after heat treatment, but it

FIG. 270.—Effect of elevated temperatures on the impact resistance of iron-nickel alloys containing 3 to 25 per cent nickel. (*Guillet and Révillon.*[74,75,83])

is impossible from his data to evaluate the effect of nickel for these materials.

The comprehensive investigation of elevated-temperature impact properties reported by Guillet and Révillon[74,75,83] included iron-nickel alloys containing 3 to 43 per cent nickel with carbon contents from less than 0.10 to about 1 per cent. Specimens were $10 \times 10 \times 60$ mm. with a U-shaped notch 2 mm. wide, 2 mm. deep, and a bottom radius of 1 mm. and were broken

in the Guillery machine. The composition and heat treatment of these alloys are shown in Table 86. Some of the more ductile specimens were unbroken by the impact; the values for these have not been given much weight in averaging and plotting the results.

The data for the five alloys containing 15 per cent or less nickel are plotted in Fig. 270. It will be noted (compare for example these investigators' curves for carbon steel or the curves given by Epstein[411]) that the curves for the alloys containing 2.99 and 7.1 per cent nickel have the same general characteristics as impact-versus-temperature curves for low-carbon steel, although from these tests it seems possible that nickel shifts the ductile range to somewhat higher temperatures. Alloys which contain considerable of the martensitic constituent (alloys C to F, Fig. 270) do not conform with the curves for low-carbon steel; the impact at room temperature is low and increases fairly uniformly

TABLE 86.—COMPOSITION AND TREATMENT OF ALLOYS TESTED*

Alloy	Composition, per cent			Treatment
	C	Mn	Ni	
A	0.09	0.15	2.99	Annealed at 850°C. (1560°F.)
B	0.16	0.20	7.10	Annealed at 600°C. (1110°F.)
C	0.13	....	12.07	Not given
D	0.22	....	12.27	Not given
E	0.11	....	15.17	Double quenched in water
F	0.17	....	20.40	Double quenched in water
G	0.79	....	25.06	Not given
H	0.12	Trace	30.00	Water quenched from 1000°C. (1830°F.)
J	0.81	0.03	29.96	Water quenched from 1000°C. (1830°F.)
K	0.18	....	42.65	Homogenized

* Guillet and Révillon.[74,75,83]

with increasing temperature. Guillet and Révillon[83] also tested an alloy containing 1.05 per cent carbon and 9.8 per cent nickel. The impact increased gradually from 4 m-kg. at room temperature and at 45°C. (115°F.) to 34 m-kg. at 675°C. (1245°F.).

180. Effect of Temperature on Properties of Iron-nickel Alloys Containing 15 to 25 Per Cent Nickel.—From the nature of the irreversible iron-nickel alloys it should be difficult to draw any definite conclusions about their properties at elevated tempera-

tures and this difficulty is increased by the scarcity of available data. The results of the four investigators who determined tensile properties at elevated temperatures are summarized in Table 87. The specimens used were rolled or forged in all cases and were air cooled before testing. Two facts stand out in these results: (1) If the material contains considerable carbon, as in the case of alloys used by Houdremont and Kallen,[258] the strength at temperatures as high as 1000 to 1050°C. (1830 to 1920°F.) is relatively high. (2) If the material is carbon free, as the alloys investigated by Yensen,[181] the strength at these temperatures is low.

Among the alloys tested at elevated temperatures by Schmidt and Jungwirth[433] were two iron-nickel alloys containing 0.03 and 0.16 per cent carbon and 24.79 and 24.33 per cent nickel. As shown in Table 103, page 442, the lower carbon alloy exhibited some brittleness when tested in tension at 650 and 760°C. (1200 and 1400°F.). A low-carbon iron-nickel alloy containing 24.17 per cent nickel and 0.40 per cent aluminum had very low elongation and reduction-of-area values when tested at 650, 760, and 870°C. (1200, 1300, and 1400°F.).

Figure 270 gives the change in impact resistance with temperature of alloys containing 20 and 25 per cent nickel (alloys *F* and *G*) as determined by Guillet and Révillon.[74,75,83] Alloy *F* was "double quenched" to produce the duplex structure; the curve for impact versus temperature follows the same contour as curves *C*, *D*, and *E* for the lower nickel alloys. No details of the treatment were given for alloy *G* except the statement that it was austenitic. The impact decreased irregularly with temperature from 35 m-kg. at room temperature to 11 m-kg. at 600°C. (1110°F.).

Bregowsky and Spring[97] determined the elevated-temperature torsional properties of an alloy containing 0.19 per cent carbon and 25.03 per cent nickel. The torsional strength and torsional proportional limit decreased uniformly from a maximum of 92,000 and 18,000 lb. per sq. in., respectively, at 40°C. (100°F.) to 43,000 and 6500 lb. per sq. in. at 315°C. (600°F.).

The properties of the irreversible alloys at subatmospheric temperatures obviously depend upon the structural changes which take place at the low temperatures; this in turn depends upon the composition and treatment. Data are given in the

Table 87.—Elevated-temperature Tensile Properties of Alloys Containing 20 to 26 Per Cent Nickel

Investigator	Composition, per cent					Testing temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Proportional limit, lb./sq. in.	Elongation,* per cent	Reduction of area, per cent
	C	Mn	Ni	Si	Ti	°C.	°F.					
Welter[177]	0.42	1.70	25.08	0.19	...	15	60	99,600	22,800	17,100	38	66
						100	210	103,800	19,900	14,200	42	60
						200	390	112,400	19,900	14,200	52	58
						300	570	95,300	18,500	12,800	37	62
						400	750	75,400	17,100	11,400	55	70
						500	930	52,600	14,200	8,500	30	76
Yensen[181]	0.01	....	20.0	0.2	0.2	500	930	63,300	23,500	.....	20.5	75
						700	1290	20,400	10,200	.....	50.0	86
						800	1470	9,200	.....	.....	60.0	75
						900	1650	7,800	5,100	.....	30.0	61
						1000	1830	5,600	4,100	.....	100.0	94
Houdremont and Kallen[268]	0.57	0.90	26.45	....	...	600	1110	49,800				
						700	1290	44,100				
						800	1470	41,200				
						900	1650	35,600				
						1000	1830	26,300				
						1050	1920	25,600				
Hatfield[279]	0.27	0.98	25.7	0.79	...	15	60	89,600	29,300	.....	52.0	70.4
						800	1470	15,900	.....	.....	34.4	28.2

* Gage lengths: Welter, 100 mm; Yensen, 1 in.; Hatfield, 1.25 in.

FIG. 271.—Effect of temperature on short-time tensile properties of 30 per cent nickel steel.

next section which show that transformation of austenite, accompanied by a marked lowering of the impact resistance, may take place at low temperatures.

181. Effect of Temperature on Properties of Iron-nickel Alloys Containing More than 25 Per Cent Nickel.—The effect of temperature on the tensile properties of alloys which are predominantly austenitic at room temperature is shown in Fig. 271. Composition and treatment of the alloys were as follows:

Investigator	Composition, per cent				Treatment
	C	Mn	Ni	Si	
Bregowsky and Spring[97]...	0.28	2.80	30.92	0.14	As rolled
MacPherran[163]...........	0.25	0.55	33.90	0.27	Annealed at 800°C. (1475°F.)
Spooner[170]..............	0.20	0.85	31.03	0.11	Annealed at 800°C. (1475°F.)
French and Tucker[186].....	0.20	0.80	28.6	0.15	Air cooled from 800°C. (1475°F.)
National Bureau of Standards[196]...............	Grade A nickel 99.99+				As rolled

Corresponding properties of 99.99+ per cent nickel, reported by the National Bureau of Standards, have been included for comparison.

Excepting the alloy used by Bregowsky and Spring,[97] which contained 2.8 per cent manganese, the austenitic alloys have apparently about the same strength at temperatures up to 305°C. (600°F.) as they have at room temperature. At higher temperatures, the tensile strength decreases uniformly with increasing temperature. Yield strength is not so strongly affected by the higher temperatures. In general, elongation is slightly lower at temperatures exceeding about 305°C. (600°F.) than at lower temperatures. There is some indication of a peak in elongation values at 260 to 305°C. (500 to 600°F.). Reduction-of-area values increase with temperature to a small maximum around 485°C. (900°F.) after which they decrease.

Portevin, Prétet, and deLacombe[577] made elevated-temperature tests of two alloys containing 0.03 and 0.08 per cent carbon

and 40.7 per cent nickel. One contained 0.02 per cent and the other 1.39 per cent manganese. The data obtained at temperatures between 800 and 1300°C. (1470 and 2370°F.) were erratic, especially for reduction of area; they indicated, however, that in general the addition of manganese improved the high-temperature strength and that it results in a marked improvement of impact resistance. The high-manganese alloy had impact values, at 900 to 1300°C. (1650 to 2370°F.), of 3 to 6 m-kg. per sq. cm.; the values for the low-manganese alloy varied between 0.5 and 2 m-kg. per sq. cm.

Impact-resistance values of the austenitic alloys H, J, and K (see Table 86 for composition) at elevated temperatures, as determined by Guillet and Révillon,[74,75,83] were so erratic that they are not plotted. Approximate values taken from the curves are as follows:

Temperature		Impact value, m-kg.		
°C.	°F.	Alloy H	Alloy J	Alloy K
Room temperature		12	22	27
200	390	22	22	20
300	570	32	18	18
400	750	16	16	18
500	930	6	10	25
600	1110	5	7	60

Chevenard[173] determined Frémont impact values of a series of alloys, mostly very low in carbon, containing 25 to 99 per cent nickel at 20, −79, and −190°C. (70, −110, and −310°F.). While he was primarily interested in studying the transformations which took place in some of the alloys at low temperature, his results are also of value in showing how ductile the austenitic alloys are at temperatures as low as liquid air. The results are given in Table 88. These indicate that low-carbon iron-nickel alloys must contain at least 42 per cent nickel to retain their full room-temperature ductility at temperatures as low as −190°C. (−310°F.). Chevenard found that carbon affected the low-temperature impact values favorably; this is shown for three of the lower nickel alloys in Table 88.

TABLE 88.—IMPACT RESISTANCE OF AUSTENITIC IRON-NICKEL ALLOYS AT LOW TEMPERATURES*

Composition, per cent			Frémont impact, m-kg. per sq. cm., at		
C	Mn	Ni	20°C. (70°F.)	−79°C. (−110°F.)	−190°C. (−310°F.)
0.06	0.32	25.9	50	11	6
0.37	0.64	25.6	45	50	8
0.08	0.41	28.9	46	18	8
0.37	1.20	27.5	49	50	18
0.08	0.39	32.0	45	32	12
0.37	1.50	31.7	50	47	34
0.08	0.47	35.3	50	34	20
0.05	0.26	37.3	47	46	22
0.09	0.36	40.0	45	49	37
0.06	0.45	42.0	43	50	50
0.12	0.52	45.7	47	52	49
0.04	0.46	47.1	51	46	46
0.06	1.50	49.4	45	52	52
0.06	0.75	57.7	45	40	52
0.04	0.59	68.4	51	45	49
0.10	0.85	77.2	49	48	52
0.05	0.39	98.7	49	48	52

* Chevenard.[173]

The results of this investigation led to the development in France of an alloy for use in machinery for liquid-air plants containing 55 to 60 per cent nickel, 1 to 3 per cent manganese, and 0.2 to 0.4 per cent carbon. At −190°C. (−310°F.) the alloy has a tensile strength of about 115,000 lb. per sq. in., an elongation of 40 per cent, a reduction of area of 55 per cent, and a Frémont impact resistance of more than 45 m-kg. per sq. cm.

E. AUTHOR'S SUMMARY

1. Iron-nickel alloys divide naturally into three groups: those containing less than 8 or 10 per cent nickel (depending upon the carbon content), in which nickel dissolves in the alpha ferrite, strengthening it; those containing 8 or 10 to some 25 or 30 per cent nickel, which are characterized by containing varying

amounts of a hard, brittle, martensitic constituent; and those containing more than about 25 or 30 per cent nickel, which are austenitic and so are not greatly affected by heat treatment. The properties of the alloys are closely related to the structure.

2. Small amounts of nickel (2 to 4 per cent), when added to iron or to iron containing low carbon, increase tensile and yield strengths, the latter more than the former (*i.e.*, yield ratio), and hardness. The elongation and reduction of area are unchanged, or in some instances lowered slightly. The impact resistance is greatly increased. If iron-carbon and iron-carbon-nickel alloys are treated to the same tensile strength, the nickel-containing material has higher yield strength, elongation, reduction of area, and impact resistance.

3. The addition of about 8 per cent nickel to iron or to steel containing less than 0.20 per cent carbon, when the alloys are hot worked, normalized, or annealed, increases the tensile strength 75 to 100 per cent, the yield strength 100 to 130 per cent, and hardness 100 to 125 per cent. The elongation is reduced 50 to 60 per cent, and the reduction of area is reduced 10 to 20 per cent. The changes are greatest for nickel additions exceeding 5 per cent. The impact resistance of iron or low-carbon steels, which is increased by small amounts of nickel, is lowered by nickel additions greater than 4 or 5 per cent, owing to the presence, even in alloys containing 5 to 8 per cent nickel, of some of the hard, brittle, martensitic constituent.

4. The change in structure of iron-nickel alloys from predominantly ferritic to predominantly martensitic is gradual, especially after annealing. As the nickel increases, hardness, tensile strength, and yield strength increase and elongation and reduction of area decrease slowly until the nickel is about 10 or 12 per cent, after which there is a more marked increase until, with alloys containing in the neighborhood of 15 to 20 per cent nickel, the strength is high, as much as 180,000 to 190,000 lb. per sq. in., and elongation and reduction of area are relatively low. Owing to the nature of the alloys containing 12 to 20 or 25 per cent nickel, the structures of which vary widely and cannot be controlled or reproduced readily, most published data on tensile or impact properties of these alloys are erratic.

5. As the nickel increases beyond 20 or 25 per cent, the amount of ductile gamma phase increases; the strength drops and the

ductility increases. Annealed alloys containing more than 30 or 35 per cent nickel are, at normal temperatures, austenitic and have properties characteristic of such materials; namely, tensile strength of 70,000 to 95,000 lb. per sq. in., yield strength of 25,000 to 45,000 lb. per sq. in., elongation of 35 to 45 per cent, and reduction of area of 60 to 70 per cent. The hardness is low and the impact resistance high.

6. Quenching iron-nickel alloys containing less than 0.10 per cent carbon and 2 to 10 per cent nickel increases the tensile and yield strengths, the latter more than the former. Elongation is reduced by quenching, but reduction of area is mostly unaffected. These changes are pronounced in the case of alloys containing 6 to 10 per cent nickel. Quenching the austenitic alloys decreases the tensile strength and increases elongation and reduction of area slightly.

7. From the few data available it appears that low-carbon nickel steels do not harden so rapidly or so much by cold work as do low-carbon steels of analogous structure. A few scattered data on the properties of cold-worked austenitic iron-nickel alloys are available. For those containing more than 30 per cent nickel, cold worked with a reduction in cross-section of 95 per cent, there is apparently a small peak in tensile strength at 65 to 80 per cent nickel. The recrystallization temperature of an iron-nickel alloy containing 40 per cent nickel, cold worked with 80 to 98.5 per cent reduction, is approximately 500°C. (930°F.).

8. The addition of up to 0.5 per cent carbon to the predominantly ferritic iron-nickel alloys (5 to 7 per cent nickel) increases, in hot-worked, normalized, or annealed specimens, tensile and yield strengths and decreases elongation and reduction of area. The addition of carbon to the irreversible alloys changes the properties to a degree dependent on the changes in structure produced by the carbon. For example, in a 15 per cent nickel alloy the maximum amount of the duplex constituent, with its accompanying brittleness, results from a carbon content of 0.20 to 0.30 per cent. Higher carbon percentages cause the formation of some austenite with lowered strength. The 25 per cent nickel iron-nickel alloy can apparently be made predominantly of duplex structure or mostly austenitic with the characteristic properties of either by varying the carbon between 0.1 and 0.6

per cent. In the austenitic alloys containing 30 to 50 per cent nickel carbon evidently increases tensile and yield strengths slightly with negligible effect on elongation and reduction of area.

9. From the limited work done on the elevated-temperature properties of iron-nickel alloys containing less than about 10 per cent nickel it is apparent that these alloys have approximately the same characteristics as low-carbon steels, namely a slight increase in strength and in impact resistance with temperature up to approximately 250 to 300°C. (480 to 570°F.) after which the tensile and impact strengths decrease with increasing temperature. Duplex and austenitic alloys have the same or slightly higher strengths at 300°C. (570°F.) than at room temperature. At higher temperatures the strength decreases uniformly. Carbon raises the temperature where the decrease begins and apparently diminishes the rate of decrease in strength with increasing temperatures. The impact resistance of duplex alloys increases slowly from a low value at atmospheric temperature to about 300°C. (570°F.), after which the increase is more rapid; these alloys become fairly ductile at temperatures of 450°C. (840°F.) and above. There are no reliable data on the elevated-temperature impact properties of the austenitic alloys.

10. One of the outstanding advantages of nickel as an alloying element is that it increases impact resistance at low temperatures; it lowers the temperature at which a rapid loss of ductility occurs and apparently lowers the rate of loss. Data are given which indicate that in a low-carbon steel, 4 to 7 per cent nickel increases the impact resistance at −45 to −100°C. (−50 to −150°F.) some 300 to 800 per cent, depending on the treatment, size and shape of specimen, notch, and other testing variables. In duplex alloys the low-temperature impact resistance depends so obviously upon the structure, which in turn depends on composition, treatment, and temperature, that reported results are of questionable value. The austenitic alloys are characterized by the complete absence of low-temperature brittleness; those containing less than 0.10 per cent carbon and more than 40 per cent nickel have the same impact resistance at −190°C. (−310°F.) as at room temperature.

CHAPTER XII

MECHANICAL PROPERTIES OF COMPLEX IRON-NICKEL ALLOYS

Relation between Structure and Properties of Iron-nickel-chromium Alloys—Mechanical Properties at Normal Temperatures—Mechanical Properties at Elevated Temperatures—Properties of Miscellaneous Complex Alloys Containing High Nickel—Author's Summary

The most important complex iron-nickel alloys are those containing chromium; of these there are three broad classes which have wide industrial application. The first and probably the most important one comprises those containing up to 5 per cent nickel and up to about 2.5 per cent chromium. Included in this class are a large number of alloys used for structural and other engineering purposes, usually containing enough carbon so that they are more properly classed as steels than as alloys. Because of the importance of these materials in engineering work, their properties are discussed in the second volume of this monograph.

The next class comprises the well-known corrosion- and heat-resisting alloys, containing between 5 and 40 per cent nickel and between 10 and 25 per cent chromium. The carbon is usually low enough so that these materials can be properly designated as alloys although most of them are commonly known as steels. These alloys are a comparatively recent development; they are the result of the pioneer investigations of Strauss and Maurer at the Krupp laboratories between 1909 and 1912 and were first patented in Germany in 1912. An excellent review of the development of these materials has been published recently.[546]

A large tonnage of the corrosion- and heat-resisting materials contains more chromium than nickel—the 18 per cent chromium, 8 per cent nickel steel is the most familiar example. Because the chromium is usually higher than the nickel, and because many of their properties are primarily dependent on the chromium, these alloys are discussed in detail in the second volume of "The Alloys of Iron and Chromium."* There is, however, an impor-

* See footnote, p. 2.

412

tant class of alloys containing approximately equal amounts of nickel and chromium, or more nickel than chromium, which have received attention in the present chapter. Many of these contain 1 to 3 per cent silicon or manganese, enough in some instances so that they could possibly be termed iron-nickel-chromium-silicon-manganese alloys. To simplify the correlation of the data, however, the properties of these alloys are included in the discussion of the properties of the iron-nickel-chromium alloys relatively low in manganese and silicon. In addition, this chapter deals with some of the data on iron-nickel and iron-nickel-chromium alloys containing relatively large amounts of manganese or tungsten, molybdenum, beryllium, boron, cobalt, and other elements.

The third class of important iron-nickel-chromium alloys are those which combine heat resistance and high electric resistivity, containing approximately 65 per cent nickel and 15 per cent each of chromium and iron. These alloys are a development resulting from the investigations of A. L. Marsh, in 1903 to 1906, on nickel-chromium alloys for thermocouples. These materials, including the nickel-chromium and the nickel-chromium-iron resistance alloys, are almost wholly responsible for domestic and industrial electric heating appliances, for heat treating in electric furnaces, and for the economical but accurate measurement of high temperatures. Some data on the heat-resistant electric-resistivity alloys containing iron are summarized in this chapter.

A. RELATION BETWEEN STRUCTURE AND PROPERTIES OF IRON-NICKEL-CHROMIUM ALLOYS

The mechanical properties of iron-nickel-chromium alloys, in common with those of other metallic materials, are related to microstructure; consequently, knowledge of this structure is of interpretive usefulness. Further, since there is also a close relation between microstructure and chemical composition, mechanical properties can, within certain limits, be predicted from the composition. Such processes, however, are unusually difficult when applied to iron-nickel-chromium alloys, because ordinary rates of cooling suppress an intermediate phase that effects far-reaching changes of microstructure when it does appear. Moreover, the structural-property relationships are usually compli-

cated by varying small amounts of carbon which are nearly always present in iron-nickel-chromium alloys.

182. Structure versus Composition of Iron-nickel-chromium Alloys.—The changes of microstructure, when the cooling rate is such that the sigma phase is suppressed, are shown vividly

FIG. 272.—Schematic low-temperature section of the iron-nickel-chromium system representing equilibrium conditions.

FIG. 273.—Schematic diagram showing the phase regions if cooling rate is such that the appearance of sigma phase is suppressed.

by a schematic low-temperature section of the phase diagram (Fig. 272)—representing equilibrium conditions—in comparison with Fig. 273, which indicates schematically and roughly the non-equilibrium phase boundaries resulting from rapid cooling. Under this condition only two phases, austenite (gamma) and ferrite (alpha), exist. Observed microstructural constituents are, therefore, only these phases, either singly or in combination.

In addition to the ease with which the intermediate sigma phase may be suppressed, the velocity of gamma-alpha transformation is low. Under certain conditions, therefore, ferrite may be precipitated from austenite by a mechanism similar to that of martensite precipitation in carbon steel; this is discussed in detail on page 36. The similarity extends to appearance under the microscope, consequently the martensite-like product is often called martensite. This usage sometimes leads to

Fig. 274.—A structural diagram for iron-nickel-chromium alloys.

difficulty, because alloys containing carbon may be able to produce the true carbide martensite. As another result of low velocity of transformation, the apparent solubility limits can vary over a wide range, depending on heat treatment, consequently a structural diagram for iron-nickel-chromium alloys can be a crude guide at best. That shown in Fig. 274 is for low-carbon alloys cooled at rates of the order of those resulting from usual mill practice. Five structural conditions are possible: I, all ferrite; II, ferrite plus the martensitic constituent; III, austenite plus the martensitic constituent (there is no real boundary between II and III, of course); IV, persistent or marginal austenite (it is thermodynamically unstable and may be transformed to

either wholly or partly by heat treatment or cold work; further, its ability to persist increases as the boundary between IV and V is approached); and V, stable austenite. Thus, the 18 per cent chromium, 8 per cent nickel composition lies within the persistent-austenite field on the side characterized by the lowest stability. This is in agreement with the common observation that ferrite can be produced in such alloys by annealing at moderate temperatures, by strain-annealing, or by cold working. Increased carbon content also increases the ease of ferrite precipitation, probably mostly because of increasing the velocity of gamma-alpha transformation. Further complication of Fig. 274 results if the carbon content exceeds the solubility limit, because of the appearance of carbide phases.

183. Structure versus Properties.—If it is assumed that the relations between composition and structure as shown in Fig. 274 are valid, the properties of the iron-nickel-chromium alloys containing small or negligible amounts of carbon may be anticipated from their composition. Those whose composition falls within fields I, II, and III will have tensile strengths ranging from relatively low to high values depending upon the amount of martensitic constituent present and upon the heat treatment. Those whose composition falls within fields II and III are generally hard and strong; the actual mechanical properties obviously depend upon the relative amounts of ferrite, martensite, and austenite present.

Alloys whose composition lies within the boundaries of fields IV and V are austenitic under normal conditions and have tensile strengths of around 85,000 to 120,000 lb. per sq. in., yield strengths of approximately 35,000 to 50,000 lb. per sq. in., and high ductility as measured by elongation, reduction of area, and resistance to single-blow impact. As noted before, alloys of marginal composition (field IV) may, under certain conditions, precipitate alpha phase. If this occurs, the strength is increased and the ductility lowered.

B. MECHANICAL PROPERTIES AT NORMAL TEMPERATURES

Except for results reported by Guillet[67] in 1906 and by Giesen[73] in 1909, few tensile-strength data could be located for iron-nickel-chromium alloys containing 4 to 9 per cent nickel and less than 10 per cent chromium, even with apprecia-

ble amounts of carbon present. Many of these alloys are essentially martensitic and are consequently hard and strong. Although the martensitic alloys are not exceptionally brittle (in the sense that a water-quenched high-carbon steel is brittle), they cannot usually be softened by annealing and are consequently unimportant industrially because of machining and other fabricating difficulties.

184. Mechanical Properties of Alloys Containing 4 to 9 Per Cent Nickel and Variable Chromium.—The alloys tested by Guillet[67] and Giesen[73] contained between 4 and 8 per cent nickel, 0 and 7.5 per cent chromium, and 0.13 and 1.05 per cent carbon. Values were reported for specimens as annealed and as water quenched. Many of them cracked in quenching. The data determined by these two investigators are primarily of historical interest now; actual values are so erratic and indicate so clearly that many of the test pieces contained internal cracks, that none are reproduced. The work of Guillet and Giesen indicated, however, nearly 30 years ago that alloys in this range of composition have in general high strength and relatively low elongation, and that some composition ranges are not responsive to annealing. As the result of these investigators' work, little attention has been paid to these alloys since.

Dickenson[134] made three series of alloys containing respectively 0, 3.75, and 5.65 per cent nickel with varying carbon and chromium contents. Small ingots were cast and forged to 2-in. bars which were water quenched from 90°C. (160°F.) above Ac_1 and tempered at 80°C. (145°F.) below this point. All his alloys contained about 0.10 per cent silicon and 0.25 per cent manganese, and all heats forged readily. Strictly considered, Dickenson's alloys should be classed as nickel steels and should, therefore, be discussed in Volume II of this monograph; however, as these properties are the only ones extant that show the effect of increasing chromium on material containing between about 4 and 9 per cent nickel, they are included in this chapter.

Under the conditions of treatment used by Dickenson his alloys showed good ductility. There was no indication (Table 89) of excessive brittleness even in specimens containing 0.50 per cent or more carbon, 3.75 or 5.65 per cent nickel, and 3.60 to 6.90 per cent chromium. There are indications that, in alloys of constant carbon and nickel, an increase in chromium increases

the strength and decreases the ductility, but the effect is not pronounced.

185. Mechanical Properties of Alloys Containing 10 to 20 Per Cent Nickel and Variable Chromium.—In addition to Guillet and

TABLE 89.—TENSILE PROPERTIES OF IRON-NICKEL-CHROMIUM-CARBON ALLOYS QUENCHED IN WATER FROM 90°C. (160°F.) ABOVE Ac_1 AND TEMPERED 80°C. (145°F.) BELOW THIS POINT*

Composition, per cent			Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
C	Ni	Cr				
0.16	3.75	0	78,400	56,000	33	74
0.13	3.75	2.10	98,600	76,200	26	73
0.26	3.75	0.80	118,700	85,200	23	66
0.22	3.75	3.30	118,700	89,600	21	64
0.38	3.75	0.50	129,900	105,200	23	60
0.35	3.75	2.90	127,700	103,000	23	66
0.49	3.75	0.85	136,600	114,200	20	56
0.45	3.75	3.80	132,100	103,000	20	59
0.40	3.75	6.00	136,600	103,000	20	60
0.50	3.75	0	118,700	73,900	24	56
0.52	3.75	4.95	136,600	107,500	20	55
0.75	3.75	0	129,900	82,900	20	51
0.77	3.75	3.65	141,100	123,200	19	52
0.76	3.75	6.90	150,100	114,200	17	65
0.28	5.65	0.80	134,400	125,500	22	63
0.27	5.65	2.40	141,100	109,800	19	59
0.43	5.65	0	127,700	100,800	20	52
0.47	5.65	4.25	150,100	123,200	18	56
0.54	5.65	1.60	147,800	123,200	20	49
0.56	5.65	5.45	153,200	123,200	16	50

* Dickenson.[134]

Giesen mentioned in the previous section, Dumas[50] was one of the pioneer investigators of the mechanical properties of iron-

TABLE 90.—MECHANICAL PROPERTIES OF IRON-NICKEL-CHROMIUM ALLOYS CONTAINING 10 TO 15 PER CENT NICKEL

Investigator	Composition, per cent					Temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation,* per cent	Reduction of area, per cent	Brinell hardness
	C	Mn	Si	Ni	Cr	°C.	°F.					
Hot rolled												
Hatfield[277]	0.11	0.34	0.21	10.16	14.84	....	....	101,300	55,100	52.0	68.1	
Annealed												
McAdam[262]	0.37	0.71	2.36	15.88	15.95	Not given		128,000	55,000	24.8	37.8	
	0.80	0.86	1.70	12.19	19.01	Not given		126,500	45,700	22.0	25.7	
Hatfield[304]	0.15	0.28	0.29	10.9	14.8	Full annealed		83,500	29,500	67	68	
Quenched†												
Mathews[118]	0.39	0.82	2.26	15.60	15.35	870	1600	136,000	80,000	32	44	270
						980	1800	130,000	68,000	39	51	250
						1095	2000	122,000	63,000	47	57	230
						1205	2200	115,000	63,000	55	62	210
						1315	2400	108,000	56,000	64	68	190
						1370	2600	104,000	55,000	67	70	180
Hatfield[277]	0.29	0.29	0.17	11.90	14.08	1150	2100	95,900	40,800	64.0	65.0	156
Johnson[357]	0.22	0.73	2.70	10.17	18.4	1120	2050	106,000	45,000	62	70	387
Page and Partridge[357]	0.34	0.67	0.85	11.76	8.7	870	1600	172,000	......	9.0	12.5	400
Scheil and Tonn[560]	0.05	....	....	10	5	Not given		......	......	....	....	220
				10	10	Not given		......	......	....	....	150
				10	15	Not given		......	......	....	....	150
				10	20	Not given		......	......	....	....	190
				10	25	Not given		......	......	....	....	190
				10	30	Not given		......	......	....	....	220

* Gage length: Hatfield, 1.25 in.; all others, 2 in.

† Mathews' specimens were oil quenched; Hatfield's and Page and Partridge's were cooled in air; Johnson's and Scheil and Tonn's were quenched in water.

TABLE 91.—MECHANICAL PROPERTIES OF HOT-ROLLED AND ANNEALED IRON-NICKEL-CHROMIUM ALLOYS CONTAINING 16 TO 20 PER CENT NICKEL AND VARIABLE CHROMIUM

Investigator	Composition, per cent					Annealing temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation,* per cent	Reduction of area, per cent
	C	Mn	Si	Ni	Cr	°C.	°F.				
Moore and Jasper[219]	0.33	0.49	1.16	19.70	8.31	940	1725	112,500	45,200†	....	52.0
MacPherran[263]	0.46	0.58	0.91	18.73	7.19	885	1625	105,600	......	33.0	53.0
Mochel, in discussion of MacPherran[263]	0.44	0.63	0.87	19.67	7.88	Not given		122,000	74,000	31.0	53.0
Hatfield[277]	0.25	0.96	2.20	17.21	23.85	Hot rolled		126,400	110,200	20.0	27.5
Clark and White[293]	0.31	0.65	0.91	20.65	7.96	Not given		93,500	23,000†	36.0	56.0
Strauss[365]	0.40	0.75	1	20	8	Hot rolled		125,000	80,000	27.0	54.0
Jenkins, Tapsell, Austin, and Rees[346]	<0.05	...	...	20.01	18.25	Hot rolled		91,200	......	14.0	
	<0.05	...	...	19.46	29.62	Hot rolled		110,900	......	21.0	
	<0.05	...	...	20.77	39.00	Hot rolled		203,900	......	7.5	
	0.43	...	...	19.97	19.11	Hot rolled		124,300	......	28.0	
	0.45	...	...	19.22	39.23	Hot rolled		164,000	......	2	
Strauss[436]	0.20	...	1	20	8	Cast		80,000‡	45,000‡	25.0‡	25.0‡

* Gage length: Jenkins et al., 1.5 in.; Hatfield, 1.25 in.; all others, 2 in.

† Proportional limit.

‡ Average properties; ranges ±5000 lb. per sq. in. tensile and yield strengths and ±5 per cent elongation and reduction of area.

nickel-chromium alloys. All three studied alloys containing 10 to 20 per cent nickel, 2 to 20 per cent chromium, and 0.30 to 1.00 per cent carbon; their determinations are, however, of little more than historical interest now.

Available data reported since 1925 are summarized in Tables 90 and 91.* As is evident, these alloys are primarily austenitic in type although there are indications that varying amounts of the martensitic constituent are present.

One of the low-carbon alloys tested by Jenkins, Tapsell, Austin, and Rees[346] (Table 91) had a strength of 203,900 lb. per sq. in. and an elongation of 7.5 per cent. According to Fig. 274, this alloy is not within the composition range where austenite is stable; it may have contained sigma phase in addition to alpha and gamma phases. It is also possible that the elongation value would have been higher if calcium instead of magnesium had been used by Jenkins *et al.* for deoxidation and desulphurization of the low-carbon alloys so that they could be forged.

The effect of quenching temperature on the mechanical properties of two alloys containing 15 per cent nickel and 18 per cent

TABLE 92.—EFFECT OF QUENCHING TEMPERATURE ON ALLOYS CONTAINING 15 PER CENT NICKEL AND 15 TO 18 PER CENT CHROMIUM*

Composition, per cent					Water quenched from		Tensile strength, lb./sq. in.	Yield strength,† lb./sq. in.	Proportional limit, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact value, ft-lb.
C	Mn	Si	Ni	Cr	°C.	°F.						
0.06	0.53	1.26	14.72	18.21	600	1110	87,000	40,000	27,500	60	66	116
					800	1470	85,600	41,500	27,000	53	64	112
					1000	1830	83,500	40,000	27,000	58	77	119
					1200	2190	76,000	34,000	21,500	69	76	101
0.10	0.44	0.06	15.09	18.07	600	1110	89,500	43,500	31,000	52	67	117
					800	1470	89,100	42,500	29,000	47	66	118
					1000	1830	87,100	43,200	25,500	51	72	118
					1200	2190	78,300	35,000	23,500	58	78	106

* Pilling.[358]
† For 0.5 per cent deformation.

* Unpublished data supplied by The International Nickel Company, Inc., on mechanical properties of iron-nickel-chromium alloys including some alloys containing 10 to 20 per cent nickel are discussed in sec. 187.

TABLE 93.—MECHANICAL PROPERTIES OF IRON-NICKEL-CHROMIUM ALLOYS CONTAINING 21 TO 25 PER CENT NICKEL AND VARIABLE CHROMIUM

Investigator	Composition, per cent						Annealed							Water quenched*						
	C	Mn	Si	Ni	Cr	Cu	Annealing temperature		Tensile strength, lb./sq.in.	Yield strength, lb./sq.in.	Elongation,† per cent	Reduction of area, per cent	Brinell hardness	Quenching temperature		Tensile strength, lb./sq.in.	Yield strength, lb./sq.in.	Elongation,† per cent	Reduction of area, per cent	Brinell hardness
							°C.	°F.						°C.	°F.					
Dumas[69]	0.25	0.48	0.23	22.80	0.21	....	Not given		165,700	78,800	19.0	31.0	....	900	1650	157,200	65,000	23.4	46.9	
	0.30	0.27	0.23	23.73	0.53	....	Not given		98,100	46,600	38.4	51.0	....	900	1650	97,700	47,200	40.7	52.0	
	0.31	0.23	0.26	24.20	5.29	....	Not given		108,400	87,500	22.5	47.0	....	900	1660	86,500	38,000	46.0	64.0	
	0.46	0.57	0.35	23.26	0.28	....	Not given		103,400	59,700	40.0	64.2	....	900	1650	90,700	50,800	46.7	76.2	
	0.60	0.52	0.28	24.80	2.59	....	Not given		125,200	85,600	33.3	60.0	....	900	1650	112,800	69,600	33.3	64.0	
	1.05	0.51	0.37	24.52	2.48	....	Not given		132,000	80,500	32.5	31.0	....	900	1650	121,600	60,000	23.5	25.0	
Giesen[73]	0.21	0.18	0.48	24.21	15.01	....	950	1740	106,700	78,200	28.0	62.0	129	850	1560	103,800	70,400	30.0	67.0	141
	0.22	0.18	0.87	25.32	15.18	....	950	1740	150,000	129,100	10.0	29.0	281	850	1560					
McAdam[203]	0.24	0.80	1.65	22.90	5.42	0.78	Not given		96,000	42,000	33.0	59.8	196							
	0.39	0.66	1.44	25.27	17.71	0.12	Not given		118,300	54,500	21.5	33.0	207							
	0.70	0.72	3.08	25.83	17.32	0.05	Not given		106,500	45,000	12.0	15.0	168							
Strauss and Talley[280]	0.39	0.37	1.07	20.91	7.57	Trace	As received		107,600	48,300‡	44.3	60.1	196	870	1600	105,200	37,100‡	33.8	57.2	205
							815	1500	108,200	49,900‡	33.3	53.3	207	980	1800	103,800	37,600‡	45.5	64.4	187
							980	1800	96,400	35,600‡	44.3	60.1	168	1095	2000	96,000	37,600‡	54.5	61.8	179
														1205	2200	94,300	38,100‡	51.5	69.1	163
														1205§	2200§	100,700	33,400‡	53.5	69.9	156

TABLE 93.—MECHANICAL PROPERTIES OF IRON-NICKEL-CHROMIUM ALLOYS CONTAINING 21 TO 25 PER CENT NICKEL AND VARIABLE CHROMIUM.—(*Continued*)

Investigator	Composition, per cent						Annealing temperature		Annealed					Water quenched*						
	C	Mn	Si	Ni	Cr	Cu	°C.	°F.	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation,† per cent	Reduction of area, per cent	Brinell hardness	Quenching temperature °C.	°F.	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation,† per cent	Reduction of area, per cent	Brinell hardness
Strauss and Talley(300) (*Continued*)	0.46	0.66	1.67	22.70	7.31	1.12	As received		110,700	57,900‡	28.0	47.3	...	650	1200	109,900	54,200‡	29.8	45.6	
														870	1600	111,200	51,900‡	27.0	41.3	174
														1040	1900	106,400	35,700‡	42.3	62.3	149
														1205	2200	95,500	30,600‡	56.0	70.8	
	0.35	0.09	2.45	25.80	16.85	......	As received		109,200	38,200‡	25.0	39.5	...	1005	2000	95,500	28,200‡	25.8	23.6	163
														1095‖	2000‖	130,100	50,900‡	21.8	31.1	235
McAdam(303)	0.24	0.39	0.56	22.14	6.04	0.82	Not given		82,500	27,500	43.0	50.0	...	1050	1920	88,800	42,100	48.0	67.0	
Hatfield(277)	0.06	0.39	0.39	24.02	23.22	......			......	......	......	......								
French, Kahlbaum, and Peterson(339)	0.24	0.53	2.96	23.3	18.05	......	790	1450	110,000	49,000	33.0	47.5								
Strauss(406)	0.50	......	1.5	22	22	......	As cast		65,000¶	53,000¶‖	7.5¶	6.5¶								

* Except Hatfield's specimen, which was air cooled.

† Gage length: Dumas and Giesen, 100 mm.; Hatfield, 1.25 in.; all others, 2 in.

‡ Reported as proportional limit.

§ 3-in. bar forged to 1 in. before heat treatment.

‖ Followed by air cooling from 705°C. (1300°F).

¶ Average properties; ranges ± 5000 lb. per sq. in. tensile and yield strengths; ± 3 per cent elongation and reduction of area.

chromium as reported by Pilling[358] is shown in Table 92. Further work by Pilling on alloys containing 10 to 20 per cent nickel is discussed in section 187.

186. Mechanical Properties of Alloys Containing 21 to 30 Per Cent Nickel and Variable Chromium.—The properties of alloys containing 21 to 25 per cent nickel and variable carbon and chromium as determined by six investigators, including Dumas and Giesen, are summarized in Table 93. As indicated by these data, the alloys are mostly austenitic although some of them apparently contain varying small amounts of the martensitic constituent, especially before water quenching. The results obtained by Strauss and Talley[204] show the effect of water quenching on alloys containing about 21 to 26 per cent nickel and 7 to 17 per cent chromium. (One of the 7 per cent chromium alloys contained copper.) The alloys with about 7 per cent chromium are clearly wholly austenitic when quenched from 1095°C. (2000°F.) or above; the one containing 17 per cent chromium and 2.45 per cent silicon, on the contrary, is not so ductile as those containing 7 per cent chromium and low silicon. The few values for the mechanical properties of alloys containing 26 to 30 per cent nickel and variable carbon and chromium are collected in Table 94.

There are too few data on alloys containing 21 to 30 per cent nickel to show clearly the effect of either chromium or carbon. Tentatively it may be assumed that chromium strengthens these alloys and makes them less ductile, although further work is necessary on alloys of constant nickel, carbon, and other elements with varying chromium to show this definitely.

187. Pilling's* Work on Austenitic Nickel-chromium Steels.— A few years ago Pilling investigated the effect of heat treatment (furnace cooling, air cooling, and water quenching from various temperatures) on the mechanical properties of sixteen commercial and eight experimental corrosion-resisting steels. Some of the steels were essentially ferritic in structure, others were martensitic; most of them, however, were austenitic including several which can be classed as marginal.

The effect of water quenching from various temperatures on the properties of three high-nickel nickel-chromium steels, two 10 to 15 per cent nickel, 15 per cent chromium steels, and two high-

* See footnote, p. 421.

TABLE 94.—MECHANICAL PROPERTIES OF IRON-NICKEL-CHROMIUM ALLOYS CONTAINING 26 TO 30 PER CENT NICKEL AND VARIABLE CHROMIUM

Investigator	Composition, per cent					Annealed							Water quenched						
	C	Mn	Si	Ni	Cr	Annealing temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation,* per cent	Reduction of area, per cent	Brinell hardness	Quenching temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation,* per cent	Reduction of area, per cent	Brinell hardness
						°C.	°F.						°C.	°F.					
Dumas[50]	0.10	0.57	0.19	28.80	0.56	Not given		76,800	47,100	35.0	65.0	...	900	1650	74,800	30,000	41.7	70.4	
	0.13	0.44	0.32	28.28	3.93	Not given		88,300	58,700	25.0	52.0	...	900	1650	74,500	33,000	45.0	64.0	
	0.21	0.54	0.29	29.88	1.91	Not given		84,500	......	29.0	57.0	...	900	1650	72,000	34,000	42.5	66.0	
	0.63	0.41	0.24	27.16	2.53	Not given		136,400	70,000	25.0	42.0	...	900	1650	121,000	56,600	41.0	49.0	
Guillet[67]	0.14	0.19	0.75	30.24	3.18	900	1650	98,100	69,700	26.0	62.0	121	850	1560	91,700	61,600	26.0	62.0	137
McAdam[308]	0.45	0.49	1.89	28.20	8.38	Not given		111,100	52,500	24.0	48.9								
Jenkins, Tapsell, Austin, and Rees[346]	<0.05	......	......	30.59	29.80	Hot rolled		122,600	......	15.0	15.0								
	0.53	......	......	29.02	29.51	Hot rolled		130,100	......	15.0	15.0								

* Gage length: Dumas and Guillet, 100 mm; Jenkins *et al.*, 1.5 in.; McAdam, 2 in.

chromium chromium-nickel steels, included for comparison, are given in Table 95. Specimens were cut from ⅞-in. round bars hot rolled from 2 or 2.5-in. rounds. Blanks, 6 in. long, were heat treated, and from these blanks standard 0.505-in. specimens were cut. Izod test pieces were standard V-notch 0.394-in.

TABLE 95.—EFFECT OF HEAT TREATMENT ON MECHANICAL PROPERTIES OF AUSTENITIC NICKEL-CHROMIUM STEELS*

Steel	Composition, per cent						Water quenched from		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Proportional limit, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Rockwell C hardness	Izod impact, ft-lb.
	C	Mn	Si	Ni	Cr	Cu	°C.	°F.							
A	0.50	0.84	2.89	24.02	8.45	1.81	Hot rolled		110,900	57,000	39,000	41.0	50.3	13	51.8
							600	1110	110,100	57,000	31,000	40.0	47.8	13	44.5
							800	1470	107,300	57,300	33,000	33.5	46.9	12	46.1
							1000	1830	105,000	49,500	24,000	39.5	54.5	7	65.5
							1200	2190	105,400	50,000	36,000	60.0	65.6	8	113.0
B	0.43	0.19	1.13	20.71	7.92	Nil	Hot rolled		111,800	55,000	44,000	48.0	59.9	7	98.1
							600	1110	110,200	55,500	36,000	51.0	57.3	10	74.6
							800	1470	111,800	55,000	34,000	42.0	54.9	10	49.4
							1000	1830	106,600	46,500	32,000	43.0	56.3	5	75.0
							1200	2190	92,500	42,500	31,000	63.0	71.5	0	114.7
C	0.28	0.20	3.00	36.80	8.44	Nil	Hot rolled		112,000	49,000	28,500	40.0	51.7	2	56.4
							600	1110	102,300	50,500	35,000	37.0	43.4	5	47.0
							800	1470	100,700	47,500	29,000	36.0	47.2	3	42.8
							1000	1830	100,900	47,000	31,000	41.0	53.6	5	59.0
							1200	2190	101,700	46,000	33,000	50.0	60.4	2	86.9
D	0.23	0.81	0.19	15.46	15.04	0.09	Hot rolled		94,600	44,500	28,000	53.0	66.2	3	96.5
							600	1110	93,800	47,000	29,000	48.5	58.3	6	82.5
							800	1470	91,600	46,000	21,500	51.0	60.6	5	82.3
							1000	1830	92,900	45,000	26,500	51.0	68.2	0	100.8
							1200	2190	86,500	36,500	20,000	67.0	73.5	-8	105.8
E	0.12	0.41	0.38	10.33	15.57	0.04	Hot rolled		100,800	47,000	26,500	59.0	67.9	13	98.3
							600	1110	101,000	44,000	14,500	58.0	61.4	13	97.5
							800	1470	105,000	40,500	20,000	55.0	64.0	15	94.0
							1000	1830	94,800	36,500	18,000	66.0	74.1	4	95.6
							1200	2190	87,000	30,000	20,000	78.0	78.9	-4	100.2
F	0.14	0.17	0.34	8.06	17.65	0.14	Hot rolled		122,300	41,000	29,500	46.0	37.2	13	102.8
							600	1110	119,200	42,500	19,000	36.0	27.5	17	109.2
							800	1470	135,200	46,000	20,000	40.0	35.0	23	98.5
							1000	1830	129,800	42,500	29,000	31.0	22.7	12	96.4
							1200	2190	121,700	33,000	24,000	50.0	38.2	13	102.0
G	0.16	0.50	0.59	7.00	19.82	0.14	Hot rolled		111,500	49,500	39,000	40.0	29.2	9	115.7
							600	1110	116,900	49,500	25,000	61.5	47.2	13	97.5
							800	1470	127,600	51,000	27,000	55.5	43.1	16	110.0
							1000	1830	128,300	48,000	34,000	35.0	25.8	16	102.3
							1200	2190	110,000	39,000	27,000	75.0	64.5	6	112.2

* Pilling, unpublished data, Research Laboratory, The International Nickel Company, Inc.

square bars, cut from 0.5-in. bars hand forged from the ⅞-in. rounds. Izod values in Table 95 are the average of two tests which checked closely. Steels *A*, *B*, *C*, *E*, *F*, and *G* were commercial materials; steel *D* was an experimental heat.

As is evident from Table 95 steels *A*, *B*, and *C* differ very little in properties. All three steels were fine-grained after quenching from 1000°C. (1830°F.) or below and were coarse-grained after quenching from 1200°C. (2190°F.). The high quenching temperature resulted in much higher elongation, reduction of area, and impact resistance for steels *A* and *B* but did not have such a marked effect on steel *C*.

Steels *D* and *E* differ chiefly in nickel content. Steel *D* is not so close to the margin of the austenite-martensite field as is steel *E*. Tensile-strength values for steel *D* are somewhat lower and were not so much affected by quenching temperatures as is the case with *E*. The impact strength of *D* is more sensitive to heat treatment, and, according to Pilling, there is no martensitization during plastic straining. Steels *F* and *G* distinctly are marginally austenitic and develop some martensite when heat treated at temperatures of 800 to 1000°C. (1470 to 1830°F.). This martensite is indicated by a noticeable increase in tensile strength but is not evidenced by any appreciable change in impact resistance. It can also be detected by magnetic methods. A noteworthy point brought out by Table 95 is that steels *A*, *B*, *C*, *D*, and *E* have higher reduction of area than elongation, while for the two higher chromium steels, *F* and *G*, the opposite is true.

Pilling also determined the properties after air or furnace cooling from the temperatures shown in Table 95. The method of cooling had very little effect, except in the case of steels *A* and *C* which had relatively low elongation, reduction of area, and impact resistance after furnace cooling from 1200°C. (2190°F.).

Other data obtained by Pilling on these high-alloy steels are discussed in sections 198, 201, and 203.

188. Mechanical Properties of Alloys Containing More than 30 Per Cent Nickel and Variable Chromium.—Of the four important classes of heat- and corrosion-resistant alloys used industrially (see Thum,[546] page 461) one contains 30 to 40 per cent nickel and 15 to 20 per cent chromium; many of the alloys of this class (as is shown later in this chapter) contain one or more

TABLE 96.—MECHANICAL PROPERTIES OF ROLLED AND ANNEALED IRON-NICKEL-CHROMIUM ALLOYS CONTAINING 31 TO 40 PER CENT NICKEL AND VARIABLE CHROMIUM

Investigator	Composition, per cent					Annealing temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation,* per cent	Reduction of area, per cent	Brinell hardness
	C	Mn	Si	Ni	Cr	°C	°F.					
McAdam[262]	0.39	1.10	0.15	34.70	10.89	Not given		112,300	67,200	28.8	46.6	
Hatfield[277]	0.35	1.36	0.21	35.15	10.90	Hot rolled		103,000	53,800	31.0	51.0	
Corfield[294]	0.50	0.70	1.52	35.55	14.95	Hot rolled		97,000	21,000†	42.0	51.0	
Greulich and Bedeschi[302]	0.28	1.88	0.15	33.61	10.10	400‡	750‡	128,000	126,000	10.0	...	285
						600	1110	128,000	121,000	10.0	...	270
						700	1290	98,200	52,600	32.0	...	250
						800	1470	98,200	51,200	31.0	...	200
						900	1650	98,200	49,700	30.0	...	145
						1000	1830	98,200	48,000	29.0	...	145
Jenkins, Tapsell, Austin, and Rees[346]	<0.05	...	...	40.03	19.10	Hot rolled		108,400	...	17.5		
	<0.05	...	...	39.60	28.87	Hot rolled		152,700	...	6.0		
	<0.05	...	...	40.54	38.00	Hot rolled		147,800	...	2.0		
	0.52	...	...	39.48	19.60	Hot rolled		128,100	...	20.0		
	0.48	...	...	39.11	30.21	Hot rolled		147,200	...	12.5		
	0.56	...	...	38.45	39.14	Hot rolled		139,600	...	14.5		
French, Kahlbaum, and Peterson[338]	0.32	1.52	0.03	34.9	12.93	Hot rolled	900	100,000	68,000	33.0	54.1	181
	0.28	1.45	0.03	35.9	11.12		1650	99,500	54,000	33.0	47.7	172
Strauss[365]				35	15	Cast		60,000		3.5	2.0	168
	0.40	1.00	1.00	40	17	Cast		65,000	50,000	1.5	1.5	241
	0.50	2.00	2.00	38	18	Cast		67,000	55,000†	2.5	4.0	185
	0.50	0.70	1.50	36	18	Cast		66,000	18,000†	6.0	3.0	240
						Hot rolled		97,000	23,000†	51.0	42.0	165
						Cast		64,200	41,200	7.0	7.8	

* Gage length: Hatfield, 1.25 in.; Jenkins et al., 1.5 in.; all others, 2 in.
† Reported as proportional limit.
‡ Greulich and Bedeschi's specimens were hot-rolled bars, water quenched, cold rolled 35 per cent, and annealed 2 hr. at the temperatures shown.

alloying elements, for example tungsten or molybdenum, in addition to nickel, chromium, and carbon, and, in some cases, also in addition to appreciable amounts of silicon and manganese.

The mechanical properties of the alloys containing 31 to 40 per cent nickel and between 2.5 and 38 per cent chromium, as reported by seven investigators, are summarized in Table 96. One of Pilling's steels (steel *C*, Table 95, page 426) discussed in the previous section is of composition within this range. These data indicate that in the hot-rolled or annealed condition alloys in this composition range are wholly austenitic; moreover, they should not respond to any quenching treatment. Pilling (see Table 95) found this to be the case for quenching temperatures of 1000°C. (1830°F.) or below. When the specimens were heated to 1200°C. (2190°F.), which resulted in coarse grain, the strength was essentially unchanged, but the elongation, reduction of area, and impact resistance were increased.

The higher strength and lower elongation values obtained by Jenkins *et al.*[346] for two of their low-carbon alloys are undoubtedly connected with their use of magnesium and with the high total alloy content, high enough so that some sigma phase may have been present, or at least so that the alloys fall outside the stable austenite field (V, Fig. 274).

Typical properties for castings reported by Strauss[365] show, as would be expected, that elongation and reduction-of-area values are low compared with the values for wrought material. The results of Greulich and Bedeschi[302] indicate that the hardness resulting from cold work persists, in some degree at least, until the alloy is annealed at 800°C. (1470°F.) or above.

Except for a few values obtained by Dumas[50] in 1902 and by Jenkins *et al.*,[346] there are no data on the mechanical properties of iron-nickel-chromium alloys containing 41 to 60 per cent nickel. It may be assumed, however, that such material would have the characteristic mechanical properties of austenitic steels.

Heat-resisting alloys containing approximately 65 per cent nickel and 15 to 20 per cent chromium are widely used. Their characteristics at room temperature are not so important as those at elevated temperature, hence there are relatively few data available. Strauss[365,436] reported average or typical properties of these high-nickel alloys in various conditions; some of his values are given in Table 97.

TABLE 97.—TYPICAL OR AVERAGE PROPERTIES OF IRON-NICKEL-CHROMIUM
ALLOYS CONTAINING ABOUT 65 PER CENT NICKEL*

Nominal composition, per cent					Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Condition
C	Mn	Si	Ni	Cr					
0.12	....	....	60	15	63,000	40,000	3	2	Castings
					100,000	60,000	25	50	Wire
			65	18	50,000	......	2	2	Castings
0.40	1.5	1.5	64	20	60,000	45,000	2	2	Castings
0.60	1.0	1.5	62	13	67,000	40,000	2.5	2.5	Castings
0.50	1.75	1.0	60	20	60,000	46,000	1.2	2.9	Castings
0.50	1.32	1.75	67	20	115,000	88,000	28	45	Hot-rolled bars
0.80	2.0	2.0	65	19	65,000	50,000	1.5	1.5	Castings

* Strauss.[365,436]

Rohn[430] found that the method of melting had an important
effect on the single-blow impact value of these high-nickel
materials. Three hundred kilograms of an alloy containing
63 per cent nickel, 15 per cent chromium, 20 per cent iron, and
2 per cent manganese was carefully melted in an electric-arc
furnace and poured into an ingot 200 mm. square; the same
amount was also melted in vacuum. Average Charpy impact
values were as follows:

	Impact resistance, m-kg. per sq. cm.
Material	
Ingot, arc melted..................................	3.4
Same, rolled to 15-mm. rod........................	11.8
Ingot, vacuum melted.............................	11.4
rolled to 15-mm. rod........................	24

**189. Miscellaneous Mechanical Properties of Iron-nickel-
chromium Alloys.**—So far as could be ascertained from a review
of the literature, little work has been done on the determination
of such properties as hardness, impact resistance, and endurance
limit. Some hardness values are given in Tables 90, 93, and 96.
In general the trend of hardness is the same as the trend of
tensile strength; alloys containing the martensitic constituent
have high strength and hardness. The hardness of the alloys

which are primarily austenitic is relatively low; it is usually 130 to 160 Brinell for those materials which, owing to either composition or heat treatment, are entirely austenitic. The presence of considerable martensite is indicated by a higher hardness number, as for example for steel F, tested by Pilling (Table 95, page 426). With alloy contents of 35 to 40 per cent of combined nickel and chromium the Brinell hardness increases somewhat, as compared with those alloys in which the combined nickel and chromium is 25 to 30 per cent. This is shown by the data of Scheil and Tonn[507] reproduced in Table 90, page 419.

Alloys which are predominantly or entirely austenitic have high impact resistance; as indicated by Pilling's data (Table 95, page 426), the average Izod impact value of such alloys is between 45 and 115 ft-lb. with values usually around 100 when the alloy is entirely austenitic. Those containing the martensitic constituent usually have low resistance to single-blow impact although Pilling's data for alloys F and G show that the impact resistance is not so sensitive to small amounts of martensite as

TABLE 98.—TENSILE PROPERTIES AND ENDURANCE LIMIT
OF IRON-NICKEL-CHROMIUM ALLOYS*

	Composition, per cent						Treatment	Tensile strength lb./sq. in.	Elongation 2 in., per cent	Reduction of area per cent	Endurance lb./s	
	C	Mn	Si	Ni	Cr	Cu						
FL	0.16	0.28	0.44	8.19	17.32	0.08	Unknown	133,000	46.8	56.3	56,000	0.42
EX	0.80	0.86	1.70	12.19	19.01	0.05	Annealed by manufacturer	126,500	22.0	25.7	65,000	0.51
EW	0.38	0.71	2.36	15.88	15.95	0.08	Annealed at 930°C. (1700°F.), furnace cooled	128,300	24.8	37.8	64,000	0.50
EV	0.39	0.66	0.14	25.27	17.71	0.01	Annealed by manufacturer	115,200	22.5	34.9	54 000	0.47
EU	0.70	0.72	3.08	25.81	17.32	0.05	Annealed by manufacturer	108,600	20.0	26.8	57 000	0.52
ES	0.24	0.80	1.65	22.90	5.42	0.78	Annealed by manufacturer	98,000	22.3	58.6	50,000	0.51
FZ	0.24	0.39	0.56	22.14	6.04	0.82	Normalized at 705°C. (1300°F.)	85,200	43.0	50.0		
ET	0.45	0.49	1.39	28.20	8.38	0.67	Annealed at 930°C. (1700°F.), furnace cooled	111,100	24.0	48.9	58 000	0.52
FK	0.39	1.10	0.15	34.70	10.	Nil	Unknown	112,300	28.8	46.6	57,000	0.51

* McAdam.[262]

the tensile strength. Pilling's results also indicate that coarse-grained alloys—as, for example, those quenched from 1200°C. (2190°F.)—have higher impact resistance than fine-grained ones.

McAdam[262] determined the endurance limit of a few iron-nickel-chromium alloys in connection with his investigations on corrosion fatigue. His data are given in Table 98. With the exception of the low value for the 18 per cent chromium, 8 per cent nickel alloy (specimen *FL*), all of his alloys have the endurance ratio of all carbon and alloy steels, 0.50 $\pm$ 0.02 to 0.05, regardless of composition or heat treatment. It may be con-cluded, therefore, that iron-nickel-chromium alloys have an endurance ratio no higher nor lower than other ferrous materials.

In an earlier investigation,[203] in which some of the steels given in Table 98 were used, McAdam determined torsional fatigue limits. The values obtained on steels *ES* and *ET* were 21,000 and 22,000 lb. per sq. in. respectively, and the ratios of torsional fatigue limit to tensile strength were 0.21 and 0.19.

190. Effect of Carbon on Iron-nickel-chromium Alloys.—It was noted in Chapter I that carbon up to 1 per cent has little effect on the forgeability of iron-nickel-chromium alloys. It does, however, increase the hardness. In an alloy containing 13 per cent nickel and 12 per cent chromium Pilling* found the following increase:

Carbon, per cent	Brinell hardness
0	128
0.10	146
0.20	162
0.30	178
0.40	190
0.50	200
0.60	208
0.70	216
0.80	220
0.90	225
1.00	230

which means that 1 per cent carbon roughly doubles the hardness. †
The effect of carbon is also marked in hardening by cold working.

* See footnote, p. 13.
† The value for 0 per cent carbon was extrapolated.

Pilling cold rolled steels containing 0.12, 0.45, and 1.02 per cent carbon, 13 per cent nickel, and 12 per cent chromium.   Results were as follows:

Carbon, per cent	Rockwell *C* hardness for a reduction by cold rolling of				
	0%	10%	20%	30%	40%
0.12	−8	16	23	28	32
0.45	5	23	32	34	38
1.02	22	35	43		

In a series of papers on carbide precipitation and intercrystalline corrosion of a 36 per cent nickel iron-nickel-chromium alloy, Chevenard and Waché[478,519,591] reported on the effect of carbide precipitation and chemical inhomogeneity on mechanical properties.   The alloy contained 0.33 per cent carbon, 36.3 per cent nickel, and 11.0 per cent chromium.   It was found that after air cooling from rolling temperatures the material was in an unstable

TABLE 99.—EFFECT OF TEMPERING AT 750°C. (1380°F.) ON MECHANICAL PROPERTIES OF A WATER-QUENCHED ALLOY CONTAINING 0.33 PER CENT CARBON, 36.3 PER CENT NICKEL, AND 11.0 PER CENT CHROMIUM*

Tempering time, hr.	Water quenched from 1200°C. (2190°F.) and tempered at 750°C. (1380°F.)				Water quenched from 1200°C. (2190°F.), cold worked "100 per cent," and tempered at 750°C. (1380°F.)			
	Tensile strength, lb./sq. in.	Yield strength,† lb./sq. in.	Elongation, per cent	Charpy impact, kg./sq. cm.	Tensile strength, lb./sq. in.	Yield strength,† lb./sq. in.	Elongation, per cent	Charpy impact, kg./sq. cm.
0	103,800	71,100	39	10	182,100	179,200	8	7
⅙	....	......	..	....	186,300	165,000	7	3.5
⅓	102,400	75,400	20	10	175,000	152,200	7	5
1	125,200	88,200	18	8	176,400	146,500	8	4.5
2	....	......	..	....	163,600	142,200	7	5.5
5	122,300	91,000	8	3.5	149,400	128,000	6	5.5
10	125,200	89,600	9	4	139,400	119,500	6	4.5
40	125,200	86,800	13	4.5	128,000	89,600	11	5
100	119,500	88,200	14	5	111,000	78,200	14	6

* Chevenard and Waché.[591]

† Reported as elastic limit.

structural condition and that, if used for certain elevated-temperature applications, carbide precipitation would take place with an increase in tensile strength and a marked lowering of the elongation. Stressing at elevated temperatures (for instance applying a pulsating load varying between 1.75 and 6.85 kg. per sq. mm. for 5 times per sec.) accelerated the precipitation of the carbide.

The effect of tempering water-quenched specimens at 750°C. (1380°F.) for various times, with and without intermediate cold working, is shown in Table 99. The data were obtained on 1.5-mm. (0.059-in.) diameter microspecimens. It was concluded that without intermediate cold working the maximum increase in strength resulted from tempering between 1 and 40 hr.; if the specimens were cold worked, the strength was at a maximum after 10 min. tempering.

As discussed later in this chapter, Chevenard et al.[590] also found precipitation hardening with great increase in yield strength, after suitable treatments, in iron-nickel alloys containing about 40 per cent nickel, to which small amounts of aluminum, vanadium, titanium, or molybdenum had been added.

C. MECHANICAL PROPERTIES AT ELEVATED TEMPERATURES

In developing iron-nickel-chromium alloys for use in applications involving elevated temperatures, especially where resistance to hot gases is an important factor, practically the whole corner of the ternary diagram, including alloys containing from about 6 to 30 per cent chromium and 0 to 40 per cent nickel, has been used commercially with varying success. Many of these materials contain considerably more chromium than nickel and are consequently discussed in some detail in "The Alloys of Iron and Chromium," Volume II.* It is well known that some of them, particularly the 18 per cent chromium, 8 per cent nickel alloy, possess certain inherent disadvantages for some applications, hence a number of other alloys containing approximately equal amounts of chromium and nickel, or more nickel than chromium, have been developed for use in those applications for which the 18-8 and like materials are not wholly adequate.

Commercial heat-resisting iron-nickel-chromium alloys usually contain less than 0.50 per cent carbon, between 0.50 and 1.25 per

* See footnote, p. 2.

cent manganese, and the same amount or more (1.50 to 2.00 per cent) silicon.

The mechanical properties at elevated temperatures of iron-nickel-chromium alloys containing equal amounts of the two elements or more nickel than chromium have been the subject of considerable study since 1920. Both short- and long-time tests have been made, but little agreement is evident in the available data; even if agreement were better, there still would be doubt about the value of the properties as determined by the various investigators, at least for engineering design. As Strauss[436] expressed it,

Short-time [elevated-temperature] tension tests determining, in a few hours, characteristics similar to those disclosed in "static" room-temperature tests may be of value to the metallurgist seeking improvement in materials or manufacturing processes, but are of limited value to the designing engineer. Methods endeavoring to predict in a hundred hours or less, the deformations that will result from many thousands of hours of use, have not yet been proved applicable to all materials or all load and temperature conditions since, in the present state of our knowledge, time-extension curves are not susceptible of mathematical expression. Quantitative design information is thus to be secured only from constant-load tests of long duration. . . . As is true today of the older and more simple steels at atmospheric temperature, present utilization [of the special alloys] must in large measure be based upon experience with similar parts under similar or identical conditions of use.

Although it is impossible to correlate the data on the iron-nickel-chromium alloys containing approximately the same amount of nickel as of chromium or more nickel than chromium, it was thought advisable to reproduce most of them so that they would at least be readily available in one place. From this collection little can be inferred on the effect of nickel or chromium on high-temperature properties, but it should give a clew to compositions which are worthy of further investigation.

191. Short-time Elevated-temperature Tensile Properties of Alloys Containing 10 to 45 Per Cent Nickel and Variable Chromium.—Data on the tensile properties of alloys containing between 10 and 45 per cent nickel and variable carbon and chromium are summarized in Table 100. Although the values obtained vary widely—owing, partly at least, to variations in testing technique—a few facts stand out. Except for the four

TABLE 100.—SHORT-TIME ELEVATED-TEMPERATURE PROPERTIES OF IRON-NICKEL-CHROMIUM ALLOYS CONTAINING 10 TO 45 PER CENT NICKEL AND VARIABLE CHROMIUM

No.	Investigator	Composition, per cent					Condition	Room temperature				315°C. (600°F.)				425°C. (800°F.)			
		C	Mn	Si	Ni	Cr		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
1	Jenkins et al.[340]	0.45	....	....	9.74	19.70	Rolled	131,000	....	28	....								
2	Hatfield[278]	0.11	0.34	0.21	10.16	14.84	Rolled	101,300	55,100	52*	68								
3	Jenkins et al.[348]	<0.05	....	....	10.80	19.06	Rolled	90,500	....	42	....								
4	Page and Partridge[337]	0.34	0.67	0.85	11.76	8.70	Air cooled	....	....	....	....	....	....	..	..	145,000	115,000	10	30
5	Hatfield[278]	0.29	0.29	0.17	11.90	14.08	Air cooled	95,900	40,800	64*	65								
6	Page and Partridge[337]	0.60	0.40	0.87	13.19	9.00	Air cooled	171,200	....	9	12	....	....	..	..	99,000	80,000	20	40
7	Pilling and Worthington[386]	0.07	0.65	1.20	14.66	18.78	Rolled	84,000	....							68,000			
8	MacPherran[363]	0.46	0.58	0.91	18.73	7.19	Annealed	105,600	....	33	53								
9	Jenkins et al.[348]	0.45	....	....	19.22	39.23	Rolled	163,900	....	2	....								
10	Hatfield[278]	0.19	0.32	0.84	19.29	20.29	Air cooled	109,300	74,400	35*	49								
11	Jenkins et al.[348]	<0.05	....	....	19.46	29.62	Rolled	112,000	....	21	....								
12	MacPherran[363]	0.44	0.63	0.87	19.67	7.88	Not given	123,000	72,000	30	53	117,000	63,000	26	43	100,000	57,000	27	48
13	Moore and Jasper[319]	0.33	0.49	1.16	19.70	8.31	Annealed	112,500	45,200†	..	52	99,900	42,800†	20	43	97,100	41,400†	20	38
14	Jenkins et al.[348]	0.43	....	....	19.97	19.11	Rolled	124,300	....	28	....								
15	Jenkins et al.[348]	<0.05	....	....	20.00	18.25	Rolled	91,200	....	18	....								
16	Clark and White[233]	0.31	0.65	0.91	20.65	7.96	Annealed	93,900	23,000†	36	56	79,000	20,000†	32	53	74,000	18,000†	30	52
17	Jenkins et al.[346]	<0.05	....	....	20.77	39.00	Rolled	203,900	....	8	....								
18	MacPherran[363]	0.53	0.58	1.25	20.78	7.42	Rolled	127,000	....	25	47	113,000	....	24	55	112,000	....	26	44
19	Kahlbaum and Jordan[417]	0.59	0.65	1.07	21.00	35.20	Cast												
20	Jenkins et al.[340]	0.48	....	....	21.08	30.60	Rolled	133,800	....	20	....								

TABLE 100.—SHORT-TIME ELEVATED-TEMPERATURE PROPERTIES OF IRON-NICKEL-CHROMIUM ALLOYS CONTAINING 10 TO 45 PER CENT NICKEL AND VARIABLE CHROMIUM.—(Continued)

No.	Investigator	Composition, per cent					Condition	Room temperature				315°C. (600°F.)				425°C. (800°F.)			
		C	Mn	Si	Ni	Cr		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
21	MacPherran[388]	0.47	0.76	1.67	21.86	7.33	Not given	108,000	63,000	48	62	102,000	48,000	52	58	94,000	43,000	46	55
22	Hatfield[279]	0.00	0.39	0.30	24.02	23.22	Air cooled	88,800	42,100	48*	67								
23	Aborn and Bain[388]	0.35	0.68	1.65	24.50	7.18	Not given	91,000	38,500	38	59					75,000	29,000	32	56
24	Jenkins et al.[346]	0.53			29.02	29.51	Rolled	130,100	......	15									
25	Kahlbaum and Jordan[447]	0.54	0.63	1.13	30.10	36.00	Cast												
26	Kahlbaum et al.[389]	0.29	1.10	0.03	34.50	10.20	Rolled	100,000	68,000	33	54								
27	Kahlbaum et al.[389]	0.40	1.16	0.05	34.80	10.24	Annealed	99,500	54,000	33	48								
28	Hatfield[279]	0.35	1.36	0.21	35.15	10.9	Rolled	103,000	53,800	31*	51								
29	Corfield[384]	0.50	0.70	1.52	35.55	14.95	Rolled	97,000	21,000†	42	51	90,000	15,000†	46	42	86,000	15,000†	42	40
30	Corfield[384]	0.50	0.70	1.52	35.55	14.95	Cast	65,000	18,000†	3	7	46,000	14,000†	2	0	45,000	14,000†	3	7
31	Pilling and Worthington[395]	0.10	1.3	0.05	36.5	16.1	Not given	108,000	......	28		93,000	....	27		88,000	....	27	
32	Kahlbaum and Jordan[447]	0.47	0.71	1.08	38.4	34.5	Cast												
33	Jenkins et al.[346]	0.55			38.45	39.14	Rolled	130,600	......	15									
34	Jenkins et al.[346]	0.48			39.11	30.21	Rolled	147,100	......	13									
35	Jenkins et al.[346]	0.52			39.48	19.60	Rolled	128,200	......	20									
36	Jenkins et al.[346]	<0.05			39.60	28.87	Rolled	152,700	......	6									
37	Jenkins et al.[346]	<0.05			40.03	19.10	Rolled	108,400	......	18									
38	Jenkins et al.[346]	<0.05			40.54	38.00	Rolled	147,800	......	2									
39	Kahlbaum and Jordan[447]	0.36	0.63	1.15	45.2	33.5	Cast												

TABLE 100.—SHORT-TIME ELEVATED-TEMPERATURE PROPERTIES OF IRON-NICKEL-CHROMIUM ALLOYS CONTAINING 10 TO 45 PER CENT NICKEL AND VARIABLE CHROMIUM.—(*Continued*)

No.	540°C. (1000°F.)				650°C. (1200°F.)				760°C. (1400°F.)				800°C. (1475°F.)				870°C. (1600°F.)			
	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
1					66,800		21						39,400		20					
2													22,800		46*	44				
3	96,000		16		42,900		18	15					27,300		64					
4		70,000		65	63,000	25,000	5‡										33,000	25,000	3‡	10
5	90,000	70,000	20	48	57,000	53,000	21	50	43,000		18	45	28,300		30*	33				
6	60,000				52,000		38	64	43,000	35,000	22	50					20,000		37	53
7									36,000		46	60					25,000		15	23
8									38,000		20	33								
9					86,300		4						53,000							
10													38,900		8*					
11					59,400		12						43,700		11	17				
12	83,000	50,000	22	44	74,600	35,800†	19	48												
13	85,500	39,000†	20	44	74,600		27		58,000	20,000†	18	48								
14					51,200		27						41,400		26					
15					48,000	7,000†	40	70					32,700		12					
16	62,000	12,000†	31	57	91,600		10		32,000	3,000†	53	80								
17					68,000		17	40					59,400		4					
18	90,000		19	45													51,000§	5,000†	3	5
19					74,600		22													
20													59,200		15					

Table 100.—Short-time Elevated-temperature Properties of Iron-Nickel-Chromium Alloys Containing 10 to 45 Per Cent Nickel and Variable Chromium.—(Continued)

No.	540°C. (1000°F.)				650°C. (1200°F.)				760°C. (1400°F.)				800°C. (1475°F.)				870°C. (1600°F.)			
	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
21	85,000	40,000	30	30					32,900	16,600	49	53	29,600		33*	38				
22																				
23	68,500	26,500	32	58	52,800	23,500	43	58					45,200		20		52,000§	6,500	5	7
24					77,100															
25	84,500	28,000†	23	33	62,000	10,000†	19	36	41,000	5,500†	24	50								
26	85,000	27,000†	22	32	61,000	8,500†	21	38	37,500	5,300†	26	52								
27																				
28	80,000	16,000†	34	32	70,000	18,000†	26	24	40,000	5,000†	40	54	30,700		46*	55	21,000		66	66
29	47,000	14,000†	4	7	49,000	13,000†	6	8	40,000	5,000†	8	15					21,000		19	32
30	84,000		25		62,000		22		35,000		25						23,000		28	
31																	43,000§	6,000	8	15
32					88,500		14						51,500		11					
33					93,000		10						49,500		13					
34					79,600		32						39,400		29					
35					99,000		4						37,700		35					
36					66,500		32						31,400		39					
37					87,600								48,000							
38																	36,000§	6,000	15	28
39																				

* In 1.25 in.   † Proportional limit.   ‡ See discussion in text.   § At 845°C. (1550°F.)

cast alloys tested by Kahlbaum and Jordan[417] (alloys 19, 25, 32, and 39) and one of the Page and Partridge[357] alloys, which was apparently a freak, the strength of these materials, regardless of whether the nickel is 15 or 35 per cent, the carbon 0.07 or 0.50, or the chromium 7 or 19 per cent, is about 25,000 lb. per sq. in. at 870°C. (1600°F.).

One of the alloys tested by Page and Partridge (alloy No. 4, Table 100) indicated brittleness at 600 and 900°C. (1110 and 1650°F.). Check determinations at 500 and 600°C. (930 and 1110°F.) yielded the following:

Determination	Temperature		Tensile strength, lb. per sq. in.	Elonga- tion in 2 in., per cent	Reduc- tion of area, per cent
	C.	°F.			
Original	500	930	116,100	18.5	69.2
Check..	500	930	121,000	17.4	67.7
Original	600	1110	76,400	4.0	15.3
Check..	600	1110	71,400	4.5	15.4

The explanation for the low elongation values of this alloy and of some of the others shown in Table 100, including the MacPherran alloy (see Table 101), may be found in the more recent investigation by Schmidt and Jungwirth discussed in the next section.

Only a few determinations have been made at temperatures higher than those given in Table 100. Pilling and Worthington,[395] MacPherran,[263] and Corfield[294] reported data obtained

TABLE 101.—TENSILE PROPERTIES OF IRON-NICKEL-CHROMIUM ALLOYS AT 980°C. (1800°F.). SEE TABLE 100 FOR COMPOSITIONS

No.	Investigator	Condi- tion	Tensile strength, lb. per sq. in.	Elonga- tion in 2 in., per cent	Reduc- tion of area, per cent
7	Pilling and Worthington[395]	Rolled	10,000	62	70
8	MacPherran[263]	Annealed	16,000	8	18
29	Corfield[294]	Rolled	12,000	60	67
30	Corfield[294]	Cast	11,000	22	44

at 980°C. (1800°F.) for alloys 7, 8, 29, and 30. Their results are given in Table 101.

Another fact which stands out in Table 100 is that the tensile strengths of a cast and of a rolled alloy of identical composition are the same at temperatures of 760°C. (1400°F.) and above (alloys 29 and 30, tested by Corfield). In general, cast alloys, regardless of the composition, have relatively low elongation and reduction of area at temperatures of 870°C. (1600°F.) or below, although the alloy tested by Corfield (alloy 30) was much more ductile than the ones tested by Kahlbaum and Jordan (alloys 19, 25, 32, and 39).

192. Blue Brittleness of Iron-chromium-nickel Alloys.—If the data given in Table 100 are carefully examined, it will be noted that there are indications of elevated-temperature brittleness in a number of the specimens, in addition to that noted by Page and Partridge. This phenomenon, known as blue brittleness, has been investigated for several austenitic alloys by Schmidt and Jungwirth.[433] The composition and room-temperature prop-

TABLE 102.—COMPOSITION AND ROOM-TEMPERATURE PROPERTIES OF HIGH-NICKEL AND NICKEL-CHROMIUM AUSTENITIC STEELS*

Steel No.	C	Mn	Si	Ni	Cr	W	Mo	Cu	V	Al	Tensile strength, lb./sq.	Elongation, l = 5d, per cent	Reduction of area, per cent
1	0.02	0.56	0.57	7.76	18.95						88,200	50.2	58.4
7	0.23	0.34	0.49	8.16	19.13				0.80		111,700	54.0	59.1
8	0.23	0.44	0.69	8.29	18.59					0.80	94,200	58.0	64.0
10	0.03	0.98	0.32	24.79							103,700	38.0	57.8
11	0.16	1.03	.33								100,300	36.0	55.0
12	0.05	0.71		18	24.17				0.40		105,700	38.0	52.3
13	0.08	0.80	0.15	24.50			2.57	1.87			75,400	24.2	36.4
15	0.41	0.94	1.15	13.50	15.82	3.89			0.40		114,100	42.0	51.0
16	0.11	0.93	0.96	18.77	22.57						89,600	45.5	64.0

* Schmidt and Jungwirth.[433]

erties of their iron-nickel alloys and high nickel-chromium steels, together with three specimens of plain and modified 18-8 materials, are given in Table 102; the results of their elevated-temperature tests are reproduced in Table 103. The specimens were quenched in water from 1000 to 1150°C. (1830 to 2100°F.)

and tempered at 750°C. (1380°F.) before testing. They were held 30 min. at the testing temperature; the time for breaking the specimens was also 30 min.

TABLE 103.—SHORT-TIME ELEVATED-TEMPERATURE PROPERTIES OF STEELS WHOSE COMPOSITIONS ARE GIVEN IN TABLE 102*

No.	650°C. (1200°F.)			760°C. (1400°F.)			870°C. (1600°F.)			980°C. (1800°F.)		
	Tensile strength, lb./sq. in.	Elongation, $l = 5d$, per cent	Reduction rea, per	Tensile strength, q. in.	Elongation, d, per tion per	El.	Tensile st. lb./sq. in.	Elongation, $l = 5d$, per		strength in.	Elongation, $l = 5d$, per cent	reduction of rea, per cent
1	38,600	22 8	36.0	24,900	18.4	26.1	13,100	10.6	13.5	7,600	29.0	27.8
7	79,700	26 0	31.1	53,500	10.0	15.3	27,900	11.2	19.0	14,500	.0	32.7
8	67,300	31 0	36.0	41,200	20.0	29.5	18,600	14.0	24.	10,900	.0	24.3
10	30,400	14 0	24.3	22,600		8	27.8 9,250	21.0	26.	5,600	34.4	36.0
11	25,900	29.0	36.0	14,100	25 0	27.8	,950	14.2	17	5,450	47.6	33.8
12	40,800		9.7	30,200		7.8	13,100	10.0	20.8	4,900	34.0	39.2
13	42,100	34.0	37.6	32,600	20.0	27.8	20,300	17.2	19 0	10,200	14.4	15.3
15	95,100	3	12.5	68,800		11.6	25,300	23.2	31.	14,500	24.4	39.2
16	65,700	32 0	38.3	44,100	26.3	32.0	21,900	24.5	25.	9,100	23 0	45.0

* Schmidt and Jungwirth.[433]

Regarding the elevated-temperature brittleness of these materials, the investigators concluded as follows:

1. All the austenitic steels examined showed brittleness at temperatures between 600 and 1000°C. (1110 and 1830°F.), the temperature of maximum brittleness varying with the composition.

2. The elevated-temperature brittleness of the 18-8 material increases slightly with carbon content; when aluminum is present, the temperature of maximum brittleness is higher than when aluminum is absent.

3. The brittleness of the high-nickel steels containing aluminum is more pronounced than when aluminum is absent.

It was found also that the speed of testing had an effect on the elevated-temperature brittleness. For example, steel 1 was water quenched and tested at 760°C. (1400°F.) with a testing speed for breaking the specimens of 1, 30, and 240 min. Results were as follows:

Testing time, min.	Tensile strength, lb. per sq. in.	Elongation, $l = 10d$, per cent	Reduction of area, per cent
1	44,900	37.4	57.4
30	24,900	18.4	26.1
240	23,800	13.6	19.0

193. Other Short-time Elevated-temperature Properties of Alloys Containing 10 to 45 Per Cent Nickel and Variable Chromium.—There are few data on the fatigue properties at elevated temperature of iron-nickel-chromium alloys containing more nickel than chromium. Moore and Jasper[219] secured the results given in Table 104 on an alloy containing about 20 per cent nickel and 8 per cent chromium. These data lead to the conclusion that the normal room-temperature endurance ratio of 0.50 ± 0.05 for all carbon and alloy steels is probably also normal for these iron-nickel-chromium alloys at temperatures up to at least 705°C. (1300°F.). Included in the large number

TABLE 104.—SHORT-TIME ELEVATED-TEMPERATURE TENSILE PROPERTIES AND ENDURANCE LIMIT OF A STEEL CONTAINING 0.33 PER CENT CARBON, 0.49 PER CENT MANGANESE, 1.16 PER CENT SILICON, 19.70 PER CENT NICKEL, AND 8.31 PER CENT CHROMIUM*

Temperature of test		Tensile strength, lb./sq. in.	Proportional limit, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Rotating beam endurance limit, lb./sq. in.
°C.	°F.					
20	70	112,500	45,200	....	52	56,000
205	400	102,000	45,600	21	48	52,000
470	875	....	......	....	..	46,000
480	900	90,800	40,100	20	40	
595	1100	80,000	35,500	19.7	44	37,000
650	1200	74,000	35,800	19.3	48	35,000
705	1300	65,400	26,200	18.5	49	30,000

* Moore and Jasper.[219]

of carbon and alloy steels that Sauveur[362] used to study behavior under torsional stress at elevated temperature were two alloys of the following composition:

Mark	Composition, per cent						
	C	Mn	Si	S	P	Ni	Cr
A	0.08	0.36	0.35	0.014	0.022	8.61	17.20
B	0.18	1.24	0.39	0.019	0.022	19.83	7.66

Square bars with a round center section, 0.5 in. long and 0.25 in. in diameter, were used. They were heated in an electric

Fɪɢ 275.—Torsional properties at elevated temperatures of iron-nickel-chromium alloys (see top of page for composition) and a high-carbon steel. (*Sauveur*.[362])

furnace for 30 min. and twisted at a uniform rate until failure occurred. Sauveur determined the load to cause failure (torsional strength), the number of complete 360-deg. twists the bar

withstood, and the factor of stiffness "obtained by dividing the stress by the strain, *i.e.*, the breaking load by the twist." Results for the two steels, together with those for a 0.88 per cent carbon steel, are given in Fig. 275.

It is to be seen that both iron-nickel-chromium alloys suffered a steady decrease in torsional strength as the temperature increased, and that the 18-8 material was, as would be expected, slightly stronger at all temperatures than the material containing 19.8 per cent nickel and 7.7 per cent chromium. Both of these alloys were markedly stronger than the plain carbon steel; this was especially noticeable at 650°C. (1200°F.).

An important fact brought out by these tests is that the higher nickel alloy *B* is decidedly tougher at temperatures of 760 to 815°C. (1400 to 1500°F.) than 18-8 (alloy *A*). The loss of ductility in 18-8 at about 735°C. (1300°F.) is a phenomenon which has been frequently noted in the past. It is possible, of course, that manganese may be a factor in the higher ductility of alloy *B*.

Sauveur also reported that the time-strain diagrams of these two steels indicate the possibility that austenitic materials of this composition may have a blue-brittle temperature range hitherto undetected. The work by Schmidt and Jungwirth (discussed in the previous section) confirms this.

194. Creep Strength of Iron-nickel-chromium Alloys Containing 10 to 45 Per Cent Nickel and Variable Chromium.—As iron-nickel-chromium alloys have been widely recommended for high-temperature service because of their strength and their freedom from scaling, considerable work has been done in an effort to determine their resistance to flow at these temperatures and to fix safe working stresses for the various alloys at the temperatures commonly encountered. Much of this work has been at moderately high temperatures on the 18 per cent chromium, 8 per cent nickel alloy. Data on this material and on alloys containing at least as much nickel as chromium have been summarized by Aborn and Bain,[369] Pilling and Worthington,[395] by various authors in "The Book of Stainless Steels,"[546] and in Volume II of "The Alloys of Iron and Chromium."*

The uncertainties connected with the long-time determination of strength properties, the danger of misinterpreting the data, the

* See footnote, p. 2.

TABLE 105.—CREEP STRESS FOR 1 PER CENT ELONGATION IN 10,000 OR 1000 HR, OF IRON-NICKEL-CHROMIUM ALLOYS

Investigator	Composition, per cent					Prior treatment	Stress, lb. per sq. in., for a testing temperature of					
	C	Mn	Si	Ni	Cr		480°C (900°F.)	540°C (1000°F.)	595°C (1100°F.)	650°C (1200°F.)	705°C (1300°F.)	760°C (1400°F.)
For an elongation of 1 per cent in 10,000 hr.												
Sisco(412)	0.08 to 0.17 per cent carbon steel					....	8,000	4,000	2,000	800		
	0.40 to 0.45 per cent carbon steel					....	8,000	4,500	2,300	1,100		
Norton(313)	0.09	0.38	0.43	8.12	18.11	Not given	......	18,000	9,500	7,000	4,000	2,500
	0.14	0.43	1.09	19.01	6.37	Not given	......	28,000	11,000	6,000	4,000	2,400
	0.59	0.32	2.22	22.50	27.52	Not given	40,000	26,000	17,000	9,000	5,000	
French, Cross, and Peterson(353)	0.21	0.53	2.96	23.40	18.10	Annealed at 790°C. (1450°F.)	22,000	14,000	8,000	4,000	1,800	800
French, Kahlbaum, and Peterson(338)	0.28	1.45	0.03	35.9	11.12	Annealed at 900°C. (1650°F.)	23,000	17,000	13,000	8,000	2,300	
For an elongation of 1 per cent in 1000 hr.*												
French, Kahlbaum, and Peterson(338)	0.15	0.35	0.22	8.46	17.32	Water quenched from 1010°C. (1850°F.)	......	31,000	18,000	9,000		
	0.24	0.50	2.96	23.30	18.05	Rolled	......	31,000	21,000	14,000		2,000
						Annealed at 790°C. (1450°F.)	......	23,000	15,000	9,000		
	0.32	1.52	0.03	34.9	12.93	Rolled	......	30,000	19,000	11,000	5,000	2,000
						Annealed at 900°C. (1650°F.)	......	24,000	16,000	9,000	5,000	3,000

* Secondary flow.

lack of precision in much of the published work, and the many factors which may affect the results have been adequately discussed by White and Clark[549] and by Sisco.[612] In brief, assuming that creep properties have been determined by the best methods known today and that the results have been properly interpreted, there still remain factors which may affect the results. Among these are—in addition to composition—melting method, grain size, prior heat treatment, and the recrystallization temperature of the particular alloy being investigated.

With full realization that the effect of such variables has not been considered by all of the investigators, a few of the principal determinations of the creep stress for 1 per cent elongation in 10,000 and 1000 hr. for various iron-nickel-chromium alloys have been correlated in Table 105, together with values for low- and medium-carbon steels from "The Alloys of Iron and Carbon," Volume II.[612] It seems possible to conclude from this collection of values that the creep strength of austenitic iron-nickel-chromium alloys, regardless of composition, falls to around 2000 lb. per sq. in. at 760°C. (1400°F.). It is also evident that at temperatures of 540 to 650°C. (1000 to 1200°F.) their creep strength is some 5 to 10 times the creep strength of carbon steels.

Some of the results reported by Norton[313] permit a comparison of the creep strength of a ferritic 13 per cent chromium stainless iron and an austenitic 19 per cent nickel, 6 per cent chromium alloy. The composition of the alloys was as follows:

Steel	Element, per cent				
	C	Mn	Si	Ni	Cr
A	0.11	0.45	0.30	0.14	13.22
B	0.14	0.43	1.09	19.01	6.37

The creep stress of these two materials for an elongation of 1 per cent in 10,000 hr. was:

Temperature		Creep stress, lb. per sq. in.	
°C.	°F.	Alloy A	Alloy B
540	1000	13,000	26,000
595	1100	5,500	11,000
650	1200	2,200	6,000
705	1300	. . . . . .	4,000

This strengthening effect of nickel is confirmed by data on castings reported by French, Kahlbaum, and Peterson[338] as shown in Table 106.

TABLE 106.—CREEP DATA ON CHILL-CAST ALLOYS TESTED AT 540°C. (1000°F.)*

Composition, per cent					Treatment			Stress for secondary flow of 1 per cent in 1000 hr , lb /sq. in.
					Temperature		Cooled in	
C	Mn	Si	Ni	Cr	°C.	°F.		
0.19	0.75	0.69	....	....	900	1650	Air	9,700
0.24	0.59	0.39	....	14.6	900	1650	Furnace	9,000
0.11	0.54	0.77	25.5	16.4	1095	2000	Air	17,000
0.11	0.59	0.87	35.4	27.2	1040	1900	Air	25,000
0.24	0.88	1.14	49.7	46.3	1040	1900	Air	25,500

* French. Kahlbaum, and Peterson.[338]

Müller-Berghaus[502] reported the creep of two iron-chromium and two iron-nickel-chromium alloys at various temperatures between 600 and 1000°C. (1110 and 1830°F.). The creep stress was defined as that load which, after a permanent elongation of 0.2 per cent, would cause a flow of 1 per cent in 10,000 hr. His data are given in Table 107. Exact compositions were not given.

TABLE 107.—CREEP OF IRON-CHROMIUM AND IRON-NICKEL-CHROMIUM ALLOYS*

Composition, per cent		Creep stress, lb. per sq. in., producing an elongation of 1 per cent in 10,000 hr. after a permanent elongation of 0.2 per cent				
Ni	Cr	600°C. (1110°F.)	700°C. (1290°F.)	800°C. (1470°F.)	900°C. (1650°F.)	1000°C. (1830°F.)
	25	8,400	2,800	600	300	
	28	5,100	2,600	400	300	150
20	25	10,000	5,400	2,700	1,300	200
35	16	9,500	6,000	3,000	1,400	250

* Müller-Berghaus.[502]

While the creep strengths obtained by Müller-Berghaus on the two iron-nickel-chromium alloys do not check with those of corresponding alloys for temperatures of 595 and 705°C. (1100 and 1300°F.) as shown in Table 105, his results confirm that nickel is necessary in iron-chromium alloys for high creep strength at these temperatures.

Tucker and Sinclair[473] determined stresses for second-stage creep of a series of cast alloys at 870°C. (1600°F.). The tests were of 500 to 700 hr. duration. Specimens were 0.25 in. in diameter with a 2-in. gage length. The results were reported as the stress to produce a creep rate of 10^{-4}, 10^{-5}, and 10^{-6} in. per in. per hr. For comparison, Tucker and Sinclair gave results on alloys of similar composition determined at 540°C. (1000°F.) by French, Kahlbaum, and Peterson.[338] Values for iron-nickel-chromium alloys for a creep rate of 10^{-6} in. per in. per hr. (1 per cent in 10,000 hr.) are reproduced in Table 108. They are especially important as they were determined on cast

TABLE 108.—SECOND-STAGE CREEP OF CAST IRON-NICKEL-CHROMIUM ALLOYS FOR AN ELONGATION OF 10^{-6} IN. PER IN. PER HR. (1 PER CENT IN 10,000 HR.) AT 540°C. (1000°F.) AND 870°C. (1600°F.)*

Alloy No.	Composition, per cent				Prior treatment: air cooled from †		Creep stress, lb. per sq. in., at	
	Mn	Si	Ni	Cr	°C.	°F.	540°C. (1000°F.)	870°C. (1600°F.)
1005	0.38	0.73	0.82	30.2	980	1800	3,600	
73	0.19	0.32	0.51	.36 27.54	980	1800	. . . . . .	400
1006	0.49	0	1.01	55.3	1040	1900	9,500	
74	0.37	0	1.13	.82 55.80	1040	1900	. . . . . .	700
1010	0.11	0.54	0.77 25.5	16.4	1095	2000	7,000	
75	0.03	0.28	0.54 24.00	17.20	1095	2000	. . . . . .	1,300
1011		59	0.87 35.4	27.2	1040	1900	11,000	
76	0.26	0.27	1.10 33.00	30.94	1040	1900	. . . . . .	2,600
1009	0.41	53	0.78 58.7	14.8	1040	1900	12,000	
77	0.33	1.00	0.51	18.02	1040	1900		1,600
DH	0.87	0.	1.10 58.45	13.72	None			2,600
OS	0.95	0.	1.77 40.42	19.18	None			2,600
MS	0.52	0.	1.57 25.18	15.62	None			1,800

* Tucker and Sinclair.[473]

† After 3 hr. at temperature, except alloys 1005 and 73 which were held 2 hr.

alloys of compositions frequently used for industrial applications where maximum oxidation resistance is desired.

The question of the relation of the results of long-time flow tests to the proper stress values for use in design is one that has not been answered definitely. Values which show the stress producing 1 per cent elongation in 10,000 hr. (1.14 years) are based upon the assumption of a regularity in flow which may or may not be the case. Extrapolation of the data obtained in a test of 700 to 1000 hr. to give values for 10,000 hr. may be justified, but the results of such extrapolation should be used with caution until more is known definitely about structural changes (for example those caused by age hardening) which may take place over long periods at high temperatures.

It has been customary to calculate safe working stresses by using 40 to 60 per cent of the creep values. Stanbery[468] made a comprehensive survey of creep data and design values collected from leading manufacturers and users of high-alloy heat-resisting materials. For alloys of the following ranges of composition: *A*, 30 to 40 per cent nickel and 15 to 20 per cent chromium and *B*, 10 to 20 per cent nickel and 25 to 30 per cent chromium he gave the following as safe working stresses at the indicated temperatures:

Working temperature		Design stress, lb. per sq. in.	
°C.	°F.	Group *A*	Group *B*
595	1100	4300 to 10000	5500 to 7500
650	1200	3800 to 8250	5100 to 6200
705	1300	3300 to 6200	4800 to 5000
760	1400	1790 to 5275	2500 to 4550
815	1500	1200 to 3100	970 to 3800
870	1600	750 to 2400	650 to 3200
925	1700	460 to 1650	380 to 1900
980	1800	290 to 1300	240 to 900
1040	1900	190 to 800	150 to 550
1095	2000	140 to 300	90 to 210

Doubtless, differences in composition are partly responsible for the variation in stress for each temperature; most of the variation, however, is caused by the widely different ideas of

engineers about the behavior of the alloys in their particular application, and to differences in the requirements which limit allowable deformation.

195. Accelerated Creep Tests of Iron-nickel-chromium Alloys. In general, as discussed in a former monograph,[612] accelerated creep tests yield data which are of little practical value. It was shown there that there is no definite relation between the values obtained by the various accelerated tests and the long-time flow

Fig. 276.—Delayed fracture tests at 650°C. (1200°F.) of a series of iron-nickel-chromium alloys showing effect of carbon, arranged by Pilling and Worthington[395] from data of Jenkins, Tapsell, Austin, and Rees.[346]

of an alloy under stress, especially at temperatures of 500°C. (930°F.) or above.

Some of the accelerated creep tests have been used effectively to detect differences in the behavior of certain lots of steel, presumably of the same composition and structure, or to survey rapidly a whole alloy system with the object of determining whether any specific alloys should be studied further.

Jenkins *et al.*[346] made good use of an accelerated creep test in their survey of wrought iron-nickel-chromium alloys containing less than 0.05 per cent and about 0.50 per cent carbon respectively. Specimens were heated to various temperatures, and various stresses were applied; the temperature and load were held

constant until failure occurred. Pilling and Worthington[395] replotted the results obtained by Jenkins *et al.;* as shown in Fig. 276 for a temperature of 650°C. (1200°F.), carbon increases the life of alloys *A, C, D,* and *E* but decreases it for alloys *B* and *F.* Figure 276 also indicates that increasing the nickel increases the life of iron-nickel-chromium alloys at 650°C. (1200°F.). For example, of the alloys containing 0.05 per cent carbon and 30 per cent chromium (*A, B,* and *C*), stressed at 20 tons (44,800 lb.) per sq. in., those with 20 per cent nickel had a life of about 4 days, those with 30 per cent nickel had a life of about 8 days, and those with 50 per cent nickel had a life of about 11 days. The corresponding figures for the 0.50 per cent carbon alloys, for the same conditions of stressing, were 7, 11, and 15 days.

196. Miscellaneous Elevated-temperature Properties.—The temperature coefficients of the elastic constants of iron-nickel alloys and one iron-nickel-chromium alloy of the elinvar type are given in Chapter V. There are a few data on the change with temperature in elastic moduli of the heat-resisting iron-nickel-chromium alloys. These are reproduced in Table 109; one low-nickel alloy is included for comparison. Chevenard's[250] data on the effect of temperature on the modulus of rigidity of iron-nickel-chromium alloys are discussed on page 115.

Robin,[78] as long ago as 1909, determined the hardness at high temperatures of two alloys: alloy *A,* containing 0.8 per cent carbon, about 23.5 per cent nickel, and 2 per cent chromium, and alloy *B,* containing 0.8 per cent carbon, 27 per cent nickel, and 4 per cent chromium. In both alloys, the manganese was approximately 0.7 per cent and the silicon about 0.2 per cent. Alloy *A* had an almost uniform hardness at all temperatures between 20 and 850°C. (70 and 1560°F.); on alloy *B,* however, the Brinell hardness number decreased slowly and uniformly from 180 at 20°C. to 95 at 850°C.

There are few data on the effect of temperature on impact resistance. Langenberg[191] made Charpy tests (keyhole notch) on an alloy containing 0.38 per cent carbon, 0.18 per cent manganese, 1.46 per cent silicon, 23.75 per cent nickel, and 7.08 per cent chromium at temperatures between −60 and 540°C. (−80 and 1000°F.). The impact resistance was uniform (within the expected experimental error) for all temperatures up to about 100°C. (210°F.); at higher temperatures it was slightly lower.

TABLE 109.—EFFECT OF TEMPERATURE ON MODULUS OF ELASTICITY OF IRON-NICKEL-CHROMIUM ALLOYS

Investigator	Composition, per cent				Prior heat treatment	Modulus of elasticity, million lb. per sq. in., at						
	C	Mn	Si	Ni	Cr		20°C. (70°F.)	200°C. (390°F.)	400°C. (750°F.)	500°C. (930°F.)	600°C. (1110°F.)	700°C. (1290°F.)
Edert[175]	0.28	0.48	0.09	5.76	20.6	Quenched in oil from 1205°C. (2200°F.)	29	26	22	20	19	14
McVetty[232], French, Cross, and Peterson[253]	0.44	0.63	0.87	19.67	7.88	Not given	24	21	22	20		
	0.21	0.53	2.96	23.4	18.10	Annealed	26	25	24	22	20	
Rawdon*	0.40	1.16	0.05	34.80	10	Rolled and annealed at 900°C. (1650°F.)	. .	. .	. .	21	18	14

* Private communication to Pilling and Worthington.[393]

The only other impact values found are those reported by Page and Partridge[357] on steels of the following composition:

Steel	Composition, per cent				
	C	Mn	Si	Ni	Cr
K	0.34	0.67	0.85	11.76	8.70
L	0.60	0.40	0.87	13.19	9.00

The specimens were air cooled from 800°C. (1470°F.), and unusual precautions were taken so that the temperature at the moment of test would be accurately measured. Izod specimens of the usual size were used. Results were as follows:

Temperature of test		Izod impact value, ft-lb.	
°C.	°F.	Steel *K*	Steel *L*
Room temperature		..	24
200	390	..	45
300	570	23	35
400	750	21	
500	930	29	35
600	1110	..	35
700	1290	43	35
800	1470	..	45
900	1650	..	58

Saffy[243] compared the impact resistance of three chromium steels containing about 0.35 per cent carbon and 7.64, 12.32, and 13.85 per cent chromium (the first two also contained 3.22 and 2.17 per cent silicon, respectively) with that of a steel containing 0.24 per cent carbon, 1.12 per cent manganese, 0.09 per cent silicon, 35.84 per cent nickel, and 11.02 per cent chromium after repeated heating to 600 and 850°C. (1110 and 1560°F.) followed by cooling and testing at room temperature. The nickel-chromium steel was the only one which was not embrittled by this treatment.

As is well known, certain of the austenitic iron-nickel-chromium alloys are subject to carbide precipitation when heat

treated in certain ways. This phenomenon and its effect on corrosion resistance have been studied extensively for the 18 per cent chromium, 8 per cent nickel alloy.

In 1931, Greulich[379] reported the results of an investigation of alloys containing 0.20 to 0.50 per cent carbon, 1.4 to 2.3 per cent manganese, less than 0.12 per cent silicon, 35 per cent nickel, and 10 to 11 per cent chromium. Water quenching after relatively long heating at temperatures of 1100°C. (2010°F.) or above followed by reheating to 650 to 750°C. (1200 to 1380°F.) caused carbide precipitation accompanied by marked increase in tensile strength (about 20 per cent) and a great increase in yield strength (nearly 100 per cent). Notched-bar impact resistance and elongation were lowered about 50 per cent. These changes were dependent in large measure upon the amount of carbon present. The changes in properties were evident also at elevated temperatures, being especially noticeable at around 450°C. (840°F.) or above. Greulich believes that carbide precipitation will permit these alloys to be used in applications where creep takes place, at a higher temperature for a given stress and rate of creep, or conversely, that they will have a lower creep rate, for a given stress and temperature, than if the alloys are treated so that carbide precipitation does not occur.

197. Elevated-temperature Properties of 65 Per Cent Nickel Electric-resistance Alloys.—The short-time elevated-temperature properties of the heat-resistant alloys of high electric resistivity, containing 60 to 78 per cent nickel, 10 to 20 per cent chromium, and in addition mostly iron, have been reported by Rohn,[242] Hatfield,[278] Pilling and Worthingon,[395] and Kayser.[418] In addition, typical properties at elevated temperatures have been summarized by Hunter.[530]

Some of the results on cast and on rolled alloys are summarized in Table 110. The ductility of the cast alloys is uniformly low, even at 1000°C. (1830°F.). The strength of these alloys is relatively high at 800°C. (1470°F.) and is usually in excess of 9000 lb. per sq. in. at 1000°C.

The properties given in Table 110 should be used with caution as the rate of loading the specimen at elevated temperature has a large effect on the strength. Kayser, for example, found an increase of about 25 per cent in tensile strength when the rate of loading was increased from 44 lb. per min. to 44 lb. in 20 sec.

TABLE 110.—SHORT-TIME ELEVATED-TEMPERATURE PROPERTIES OF IRON-NICKEL-CHROMIUM ALLOYS CONTAINING ABOUT 60 PER CENT NICKEL

Investigator	Composition, per cent					Condition	Room temperature				800°C. (1470°F.)				1000°C. (1830°F.)			
	C	Mn	Si	Ni	Cr		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
Pilling and Worthington[395]	0.7	0.6	0.5	60.7	13.0	Cast	62,000	......	2	..	35,000	......	2	..	18,000	......	2	..
Kayser[448]	0.9	....	....	66	21	Cast	63,000	47,000	2.5	2.4	21,000	......	6	5.6	9,000	......	7.5	16
	0.8	....	....	60	20	Cast	69,000	54,000	1.5	1.4	26,300	......	8	4.8	11,800	......	11	9.6
Hunter[330]	0.16	0.07	2.36	09.86	14.06	Cast	41,000	24,000*	3	5	26,000	7,000*	3	7	10,000	3,000*	3	7
	0.87	0.86	1.10	58.45	13.72	Cast	65,000	20,000*	2	2	36,000	13,000*	2	2	16,000	5,000*	7	7
Hatfield[373]	0.06	0.89	0.71	60.4	11.6	Rolled	122,400	73,900	26	30	34,300	......	38	43				
Pilling and Worthington[395]	0.81	1.50	0.58	66	12.8	Rolled	108,000	......	30	48	17,000	......	30	40	6,000	......	45	60
	0.29	1.80	0.87	65.05	11.7	Rolled	107,000	52,000*	..	..	50,000	......	:	:	16,000			
Kayser[448]	0.7	....	....	57	15	Rolled sheet	65,000	35,800	18	58	26,900	......	38	42	9,600	......	31	27.2

* Proportional limit.

There are few data on the creep strength of these alloys. Most of the information available was obtained on material containing no iron or containing considerable amounts of manganese, copper (probably present as an impurity), or tungsten. French, Kahlbaum, and Peterson[338] determined stresses for a rate of flow of 1 per cent in 10,000 hr. on three such alloys. The compositions and heat treatments, together with those for two other alloys included for comparison (alloy *D* was tested by French, Cross, and Peterson[253]), are as follows:

Alloy	Composition, per cent							Heat treatment
	C	Mn	Si	Ni	Cr	W	Cu	
A	0.31	2.79	0.27	76.0	18.8	....	0.66	Annealed at 1040°C. (1900°F.)
B	0.20	1.66	0.08	57.4	10.34	3.30	....	Annealed at 900°C. (1650°F.)
C	0.25	1.40	0.06	60.8	10.75	2.8	....	Casting, annealed at 900°C. (1650°F.)
D	0.28	0.38	0.17	....	20.5	....	0.98	Water quenched from 980°C. (1800°F.), tempered at 650°C. (1200°F.)
E	0.15	0.35	0.22	8.46	17.32	....	....	Not given

Results are given in Table 111. Noteworthy is the low creep strength of the high-nickel alloy *A*, which is practically iron-free.

TABLE 111.—CREEP STRESS FOR ELONGATION OF 1 PER CENT IN 10,000 HR. OF HIGH-NICKEL IRON-NICKEL-CHROMIUM ALLOYS

Temperature of test		Stress for flow of 1 per cent in 10,000 hr.				
°C.	°F.	*A**	*B**	*C**	*D*†	*E**
425	800	......	......	......	18,000	
480	900	13,000	......	13,000	10,000	
540	1000	5,000	30,000	12,000	6,000	11,000
595	1100	2,600	17,000	10,000	3,000	11,000
650	1200	1,600	6,000	9,000	1,600	10,000
705	1300	850	1,900	7,500	......	7,000
760	1400	400	600‡	5,500	......	4,000

* French, Kahlbaum, and Peterson.[338]
† French, Cross, and Peterson.[253]
‡ At 730°C. (1350°F.).

Two of the alloys tested by Tucker and Sinclair (alloys 1009 and *DH*) had compositions corresponding to that of the high-nickel electric-resistance alloys. Their creep strength is given in Table 108, page 449.

D. PROPERTIES OF MISCELLANEOUS COMPLEX ALLOYS CONTAINING HIGH NICKEL

In the past 40 years, most of the alloying elements which could be readily procured have been added to iron-nickel or iron-nickel-chromium alloys or to nickel or nickel-chromium steels, and the resulting properties have been studied more or less completely. Many of the data—on the effect of molybdenum, silicon, tungsten, copper, chromium, manganese, and vanadium—have been correlated and summarized in monographs of this series already published or in preparation. More of them—on the complex nickel structural and engineering steels—will be discussed in the second volume of this monograph. Therefore, it is only necessary here to discuss the effect of various elements on the properties of alloys relatively high in nickel, giving a general idea of the characteristics of those alloys which are discussed in detail in another monograph, and devoting more attention to those alloying elements not so commonly used.

198. Manganese in High-nickel Alloys.—Some of the earliest investigations on alloys of iron were made on materials containing relatively large percentages of nickel and manganese. Among the early workers in this field Dumas,[50] Hadfield,[52,62] and Guillet[61] should be mentioned. Dumas found that water quenching an alloy containing 0.25 per cent carbon, 11.68 per cent nickel, and 6.43 per cent manganese reduced the strength (from 107,000 to 89,000 lb. per sq. in.) and increased the elongation slightly (from 25 to 26.7 per cent). Hadfield[52] reported that a rolled alloy containing 0.60 per cent carbon, 14.55 per cent nickel, and 5.04 per cent manganese had a strength of 112,-000 lb. per sq. in. with 70 per cent elongation after water quenching from 1100°C. (2010°F.).

The work of Hadfield[62] and Guillet[61] reported in 1905 indicated that steels containing more than 12 per cent nickel and 8 per cent manganese (5 per cent manganese with higher nickel) were austenitic and had tensile strengths between 90,000 and 130,000 lb. per sq. in. with elongation values between 30 and

70 per cent in 2 in. One of Hadfield's alloys (0.83 per cent carbon, 14.44 per cent nickel, 5.90 per cent manganese, and 2.25 per cent copper) showed exceptional properties at low temperature. The specimens were from a forged bar and were quenched in water from 1050°C. (1920°F.). Properties were as follows:

Temperature of test	Tensile strength, lb. per sq. in.	Elongation in 2 in., per cent
Room temperature.......	109,800	50
Liquid air..............	165,800	40

Hadfield and Guillet both found that alloys containing less than 12 per cent nickel and 5 per cent manganese were brittle. This is to be expected.

After 1905 the austenitic iron-nickel-manganese alloys aroused comparatively little interest. Ever since the early work of Hadfield and Guillet it has been well known that manganese favors strongly the retention of austenite; as a result it is possible to replace a part of the nickel in austenitic alloys by manganese. It is, however, necessary to limit the carbon content if satisfactory hot- and cold-working properties are to be assured; hence, low-carbon ferromanganese must be used. Because of the cost of the low-carbon manganese alloys the successful use of this element as a substitute for nickel in austenitic corrosion-resistant alloys is an economic problem the discussion of which is not within the field of this monograph. The corrosion of the alloys containing manganese is also an important factor. High-manganese alloy steels and the effect of manganese in the high-chromium stainless steels are discussed in more detail in other monographs of this series.*

It was noted in Chapter I that according to unpublished data by Pilling† the maximum manganese in the low-carbon alloys consistent with good hot- and cold-working properties is 9 per cent, and with this amount the nickel content necessary for an

* "The Alloys of Iron and Chromium, Vol. II.—High-chromium Alloys" (to be published soon); and "The Alloys of Iron and Manganese" (in preparation).

† See footnote, p. 13.

austenitic material may be reduced from 26 to about 10 per cent. Pilling also determined the hardness of a series of low-carbon nickel-manganese steels and of iron-nickel-copper-manganese alloys. Results are shown in Table 112. He concluded that

. . . the introduction of manganese in quantity to marginal austenitic alloys with nickel and copper permits a progressive increase in the iron content and corresponding decrease in the total alloy content without the formation of air-hardening martensitic alloys. Manganese is about 1.9 times as effective as nickel in inducing the retention of the austenitic state while copper is inert, and all three preserve their respective powers in this regard when present in combination.

TABLE 112.—BRINELL HARDNESS OF NICKEL-MANGANESE AND NICKEL-MANGANESE-COPPER STEELS*

Alloy No.	Composition, per cent					Brinell hardness		
	C	Mn	Si	Ni	Cu	As forged	Air cooled from 1000°C. (1830°F.)	Furnace cooled from 1000°C. (1830°F.)
404	0.22	14.20	0.23	0†	....	259	219	
701	Low	14.0†	....	0†	....	219‡	218	218
702	Low	16.0†	....	0†	....	229‡	237	228
412	0.11	11.50	0.09	5.58	....	....	205	204
396	0.07	12.40	0.16	12.3†	....	147	107	
407	0.09	9.10	0.12	8.72	....	164	150	
408	0.07	8.95	0.13	8.94	....	120	112	
411	0.11	7.72	0.10	11.25	....	....	117	
395	0.17	6.55	0.10	17.30	....	136	105	
413	0.17	6.32	0.05	16.29	....	....	99	
410	0.10	3.26	0.02	21.20	....	....	111	
388	0.19	11.65	0.28	8.8†	3.7†	129	111	
390	0.18	14.20	0.25	7.0†	3.0†	144	119	
391	0.16	9.55	0.18	10.5†	4.5†	146	111	
392	0.10	6.80	0.16	12.2†	5.3†	141	110	
393	0.10	4.46	0.05	14.0†	6.0†	226	249	
403	0.15	13.10	0.26	3.2†	1.3†	218	217	

* Pilling, unpublished data, Research Laboratory, The International Nickel Company Inc.

† Not determined by analysis. Percentage given is the amount added.

‡ Water quenched.

For the austenitic alloys containing 75 per cent iron, Pilling's results indicate that manganese up to 15 per cent does not increase hardness; in the marginal austenitic iron-nickel-manganese alloys manganese does not increase the hardness until it exceeds 10 per cent.

A few years ago Hensel[382] used iron-nickel-manganese alloys to study the age hardening of austenite. The principal object of his work was to produce a hard, non-magnetic material by the heat treatment of austenitic steels. The base alloy contained 15 per cent nickel, 10 per cent manganese, and practically no carbon. Titanium and molybdenum were added as age-hardeners. No values were reported for the tensile properties of the iron-nickel-manganese alloy containing neither titanium nor molybdenum.

Precipitation hardening resulted from the heat treatment and aging of those alloys containing 3 to 5 per cent titanium or more than 15 per cent molybdenum. The effect of titanium addition is shown in Table 113. Results with the alloys containing molybdenum were not so satisfactory. In the latter instance, the proportional limit was lowered somewhat by aging, and the ductility was lowered greatly without a corresponding increase in tensile strength.

TABLE 113.—TENSILE PROPERTIES OF AN ALLOY CONTAINING 15.37 PER CENT NICKEL, 9.94 PER CENT MANGANESE, 4.15 PER CENT TITANIUM, AND 0.73 PER CENT SILICON AFTER WATER QUENCHING FROM 1000°C. (1830°F.) AND AGING AT 600°C. (1110°F.)*

Aging time, hr.	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Proportional limit, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Brinell hardness
Not aged	89,300	45,000	16,500	33	35.2	166
50	139,800	101,800	56,000	45	5.9	321
120	156,500	107,000	70,000	13.5	13.8	331
280	158,800	111,000	45,000	10.2	11.5	341

* Hensel.[382]

As is evident from the chemical composition of some of the alloys given in the previous sections, 1 to 1.5 per cent manganese is frequently added to the iron-nickel-chromium alloys to increase

their forgeability by changing the distribution of the sulphides present.

199. Cobalt in High-nickel Alloys.—Hessenbruch[599] investigated the effect of annealing on a cold-worked alloy containing 27.3 per cent nickel, 19.0 per cent cobalt, and 0.6 per cent manganese. Annealed 12-mm. (0.472-in.) rods were cold rolled to 8 mm. (0.315 in.), and two specimens were heated 15 min. at temperatures between 100 and 1300°C. (210 and 2370°F.). One specimen was cooled slowly and the other one quenched from these temperatures. The resulting Brinell hardness numbers were as follows:

Annealing temperature		Brinell hardness after	
°C.	°F.	Slow cooling	Quenching
100	210	310	275
200	390	310	280
300	570	310	290
400	750	320	325
500	930	350	345
600	1110	310	295
700	1290	160	160
800	1470	150	150
900	1650	145	145
1000	1830	140	140
1100	2010	135	135
1200	2190	135	140
1300	2370	145	140

The hardness after quenching from 900°C. (1650°F.) or above can be increased by increasing the time the specimen is held at temperature before quenching. Thus, holding for 15 min. at 1200°C. (2190°F.) and quenching resulted in a hardness of 140 while holding for 1 or 2 hr. before quenching resulted in a hardness of 190.

The results of an extensive investigation of the properties at normal and elevated temperatures of iron-nickel-cobalt alloys precipitation hardened with titanium were reported in 1932 by Austin and Halliwell.[404] Alloys of various compositions, many of them containing 3 per cent or less iron, were made in 2-kg. (4.4-lb.) melts and chill cast as 2-in. square bars. These bars

were forged to 0.5- or 1-in. squares and heated 1 hr. at 950°C. (1740°F.) followed by water quenching. They were then aged 72 hr. in vacuum at 650°C. (1200°F.) followed by quenching in water.

The properties of some of the alloys are given in Table 114. Austin and Halliwell also tabulated typical properties at room temperature and at 650°C. (1200°F.) of a number of commercial heat-resisting alloys as previously published by other investigators. Summarizing, they wrote:

The highest proportional limit at 600°C. (1110°F.) of the [heat resisting] commercial alloys is about 25,000 lb. per sq. in. Among the new alloys proportional limits between 50,000 and 70,000 are recorded, although in some cases the ductility is low. One of the most promising alloys appears to be the one designated 42*B*, which at 600°C. has a proportional limit of 57,000 lb. per sq. in., 21 per cent elongation, and 21 per cent reduction of area. A comparison of the tensile strength of this alloy with the 70:30 nickel-chromium alloy . . . shows an apparent marked superiority for the new alloy. In 42*B* the ultimates at normal temperature and at 600°C. are 165,000 and 127,000 lb. respectively. In the 70:30 alloy at normal temperature and at 650°C. (1200°F.) they are 153,000 and 105,000 lb. respectively.

200. Titanium in High-nickel Alloys.—The precipitation hardening of high-nickel alloys by titanium and other elements has received considerable attention in recent years. The investigations by Hensel[382] on iron-nickel-manganese alloys and by Austin and Halliwell[404] on iron-nickel-cobalt alloys, precipitation hardened with titanium, are discussed in the previous two sections. Chevenard, Huguenin, Waché, and Villachon[590] recently reported that the addition of small amounts of vanadium, molybdenum, titanium, and especially aluminum to the austenitic alloys results, after suitable treatment, in greatly increased yield strength. For example, an alloy containing 40 per cent nickel, 2 per cent aluminum, and 2 per cent titanium, if quenched from a high temperature, cold worked, and reheated for a few hours at 600 to 650°C. (1110 to 1200°F.), had an elastic limit of about 200,000 lb. per sq. in. determined on a microspecimen.

Although not dealing specifically with iron-nickel alloys, an investigation by Wasmuht[401] showed the relation between nickel (and other alloys) and the age hardenability of steels containing titanium. Wasmuht added nickel (1, 3, and 6 per cent), silicon (1.5, 2, and 3.5 per cent), chromium (3, 4.5, 9, 16.5, and

TABLE 114.—ROOM-TEMPERATURE AND ELEVATED-TEMPERATURE PROPERTIES OF IRON-NICKEL-COBALT ALLOYS CONTAINING TITANIUM*

Alloy No.	Composition, per cent						Room temperature					600°C. (1110°F.)				
	Ni	Co	Cr	Fe	Ti	Mo	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Proportional limit, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Proportional limit, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
0	73.3	17.3	......	6.25	2.4	.....	108,000	58,000	27,500	35.0	59.5	76,800	46,800	15,000	24.7	33.2
21†	57.9	33.1	......	6.34	2.58	.....	137,100	83,600	45,000	35.0	59.5	105,000	81,600	52,000	24.7	33.2
42B	46.1	24.86	18.74	7.02	2.19	.....	164,750	104,000	70,000	29.0	37.0	127,100	86,000	57,500	21.5	21.7
55	22.86	40.38	......	34.04	2.23	.....	145,000	99,500	57,500	18.0	42.0	107,700	89,500	37,500	11.0	16.0
69	23.19	39.94	......	33.4	2.24	.....	135,000	100,000	50,000	17.6	48.5	103,100	78,000	32,500	11.1	20.4
43	50.98	28.66	1.14	15.5	3.14	.....	159,000	109,000	72,500	12.0	15.6	119,500	97,150	41,200	5.0	10.0
51	28.93	19.73	......	44.70	2.39	.....	157,700	123,500	67,500	16.3	46.3	113,500	90,000	44,000	6.5	9.8
62B	32.68	40.23	......	23.95	2.19	10.4	168,000	114,500	80,000	23.6	41.6	119,000	97,000	43,700	6.5	17.0
57	67.6	14.64	......	14.52	2.5	.....	156,700	92,000	65,000	28.6	38.0	92,000	81,400	46,200	2.3	11.0
58	47.7	15.64	......	33.52	2.21	.....	149,000	103,000	55,000	28.6	38.0	112,500	86,500	37,200	2.3	10.5
52	40.15	40.93	......	15.85	2.44	.....	170,000	114,000	80,000	22.0	44.6	130,500	105,000	37,800	4.1	9.3
61	5.07	19.05	......	72.44	2.51	.....	154,000	120,000	95,000	...	3.1	47,500	38,200	12,500	4.6	4.7
68‡	70	......	......	27.5	2.5	.....	150,250	97,000	65,000	15.5	20.4	100,000	92,000	49,500	4.0	5.3
73‡	20	20	......	57.5	2.5	.....	167,750	125,000	75,000	18.0	29.0	76,500	48,500	16,000	37.5	72.0

* Austin and Halliwell.(46)
† Aged 100 hr.
‡ Nominal composition.

17.5 per cent), aluminum, and manganese to a low-carbon steel containing 3 per cent titanium. Of the alloys used, silicon had the greatest effect on precipitation hardening; nickel was effective, but only one-half or one-third as much as silicon. Chromium, manganese, and aluminum had no appreciable effect.

Kroll[351] studied in detail the age-hardening properties of iron-nickel-titanium and iron-nickel-chromium-titanium alloys. High-purity alloys were quenched from 950°C. (1740°F.) and aged at 500°C. (930°F.) for 12 hr. After this treatment the Brinell hardness number of iron-nickel-titanium alloys increased with nickel until it reached a maximum at about 12 per cent nickel. With nickel contents of 25 per cent or higher, the hardness decreased greatly. As an example of the effect of aging, an alloy containing 13 per cent nickel and 3.75 per cent titanium may be cited; it had a hardness value of 260 after quenching and of 480 after aging. Iron-chromium-nickel alloys of the 18-8 type age if titanium is added. Kroll took special precautions such as using high-purity iron and nickel, titanium made from titanium tetrachloride, and melting in an atmosphere of argon, to insure that the aging was not influenced by carbon or nitrogen.

201. Pilling and Merica's Work on Precipitation Hardening of Austenitic Nickel Steels by Titanium.—The effect of titanium on the tensile and impact properties of a number of austenitic nickel, nickel-chromium, and nickel-copper steels after a variety of treatments was determined by Pilling and Merica.* Exploratory tests were made on binary iron-nickel alloys melted from ingot iron, electrolytic nickel, and essentially carbon-free ferrotitanium and nickel-titanium. The titanium alloys used were made by the thermit process and contained one-sixth to one-fourth as much aluminum as titanium; that means that in adding, for example, 1 per cent titanium to the alloy, 0.15 to 0.25 per cent aluminum was added simultaneously.

It was found that titanium causes the formation of a very hard constituent, the composition of which is at present unknown. Pilling and Merica determined, very roughly, the solubility of titanium in iron-nickel alloys at 1000°C. (1830°F.) and found that it varied from somewhat less than 6 per cent titanium for an alloy containing about 25 per cent nickel to about 1.75 per cent titanium for a 70 per cent nickel alloy. In general, the alloys

* See footnote, p. 13.

containing more than these amounts of nickel and titanium were forgeable with difficulty or could not be forged at all. From these preliminary tests it was concluded that in the range of 30 to 50 per cent nickel the optimum titanium additions were 2.2 to 3.0 per cent.

Some typical hardness determinations on a 35 per cent nickel alloy and the accompanying forging properties were as follows:

Composition, per cent			Forgeability at 1170°C. (2140°F.)	Brinell hardness, after			
C	Ni	Ti		Water quench-ing*	Air cooling*	Furnace cooling*	Water quenching* and reheat-ing 3 hr. at 700°C. (1290°F.)
0.03	34.78	0.49	Good	132	131	129	138
0.03	34.74	1.31	Good	144	137	156	197
0.01	35.29	2.16	Good	154	142	300	304
0.03	34.79	2.20	Good	149	151	321	307
0.05	33.85	4.00	Fair, head split	165	268	342	371
0.07	33.23	6.71	Poor, broke	199	393	385	380

* From 1000°C. (1830°F.).

The data obtained in this exploratory investigation led to an investigation of the effect of titanium on some austenitic nickel steels containing chromium or copper. Representative results are given in Table 115. It should be remembered that all three of these steels contained between 0.7 and 0.9 per cent manganese and approximately one-fourth as much aluminum as titanium. In the soft condition, as hot rolled, or as air or water quenched, these steels had properties conforming closely to those of other austenitic nickel-chromium or nickel-copper steels of the same type. It is evident that the presence of titanium has little or no effect on the mechanical properties in the hot-rolled or air- or water-quenched condition.

For age hardening steel M, two treatments were used, selected from a series of pilot tests for hardness. One consisted of relatively short tempering at 650 to 700°C. (1200 to 1290°F.) followed by air or water cooling; the other one was an incremental treatment whereby the steel was tempered 3 hr. at 675 or 700°C.

TABLE 115.—EFFECT OF TITANIUM ON AUSTENITIC NICKEL-CHROMIUM AND NICKEL-COPPER STEELS*

Quenching temperature		Quench-ing medium	Tempering			Cooled in	Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Propor-tional limit, lb./sq. in.	Elonga-tion in 2 in., per cent	Reduc-tion of area, per cent	Hard-ness†	Izod impact, ft-lb.
°C.	°F.		Temperature		Time, hr.								
			°C.	°F.									
Steel *A*—0.07 per cent carbon, 30.10 per cent nickel, 7.99 per cent copper, 2.50 per cent titanium													
900	1650	Water	...	...	..	....	87,600	......	24,800	37.5	65.1	147	
900	1650	Air	700	1290	4	‡	192,000	......	110,000	16.0	33.0	384	
Steel *B*—0.07 per cent carbon, 21.73 per cent nickel, 6.30 per cent chromium, 2.35 per cent titanium													
900	1650	Water	...	...	..	....	87,800	......	34,600	35.0	59.8	165	
900	1650	Air	700	1290	4	‡	158,000	......	77,400	22.0	47.8	306	
Steel *M*—0.18 per cent carbon, 15.12 per cent nickel, 12.64 per cent chromium, 2.37 per cent titanium													
Hot rolled													
800	1470	Air	...	...	..	....	90,900	42,000	24,000	48.0	67.7	-2	82.8
800	1470	Water	...	...	..	....	93,300	41,500	20,000	49.0	65.4	-2	88.8
1000	1830	Air	...	...	..	....	89,000	40,000	24,000	48.0	66.6	-3	99.5
1000	1830	Water	...	...	..	....	89,700	40,000	25,000	49.0	67.9	-8	98.5
1000	1830	Water	...	...	..	Air	87,200	40,000	23,000	48.0	68.2	-2	102.5
1000	1830	Water	700	1290	3	Air	130,000	75,000	60,000	37.0	61.1	18	84.0
1000	1830	Water	700	1290	3	Water	130,000	76,000	70,000	37.0	62.1	20	76.5
1000	1830	Air	675	1245	3	Water	136,800	75,000	55,000	38.0	58.5	16	100.0
1000	1830	Air	675	1245	6	Water	136,800	72,500	52,000	37.0	54.1	18	87.0
1000	1830	Air	650	1200	6	Water	131,700	72,000	52,000	40.0	59.1	18	81.0
1200	2190	Air	...	...	..	....	82,500	31,000	16,000	55.0	67.7	-11	93.5
1200	2190	Water	...	...	..	....	80,700	35,000	23,500	55.0	71.7	-11	99.0

* Pilling and Merica, unpublished data, Research Laboratory, The International Nickel Company, Inc.

† Steels *A* and *B*, Brinell hardness; steel *M*, Rockwell *C* hardness.

‡ Cooled in the furnace from 700 to 600°C. (1290 to 1110°F.), held 12 hr. at 600°C. (1110°F.) and cooled in air.

(1245 or 1290°F.), cooled very slowly to 625 or 650°C. (1155 or 1200°F.), held 3 hr. more, cooled very slowly to 550 or 600°C. (1020 or 1110°F.), held 3 hr. more, and then cooled in air or the furnace to room temperature. The effect of the short-time tempering is shown in Table 115; the result of the incremental treatment was to increase the strength and decrease the ductility. Rounded values were given as follows:

Property	Soft condition, air or water cooled	Tempered at 700°C. (1290°F.)	Incremental treatment
Tensile strength, lb. per sq. in.........	90,000	130,000	170,000
Yield strength, lb. per sq. in..........	40,000	75,000	95,000
Proportional limit, lb. per sq. in.......	22,000	65,000	80,000
Elongation in 2 in., per cent..........	48	38	25
Reduction of area, per cent...........	68	62	25
Izod impact, ft-lb....................	100	80	20

According to Pilling and Merica "these precipitation-hardened austenitic nickel-chromium-titanium steels are excelled elastically by the stainless chromium steels and, by a small margin, by some of the hardenable nickel-chromium steels, but for equal degrees of ductility or toughness no other corrosion-resistant steel yet examined has such a high proportional limit."

202. Boron, Beryllium, and Gallium in High-nickel Alloys.— The effect of nickel and boron on the hardness of iron was investigated and reported in 1915 by Tchijevsky and Mikhailovsky.[119] A systematic survey was made of one corner of the ternary diagram; the alloys contained 0 to 25 per cent nickel and 0 to 5 per cent boron and were melted from high-purity metals. The melts were held molten 20 min., stirred with a quartz rod, and cast into cylinders 40 mm. (1.575 in.) long and 15 mm. (0.591 in.) in diameter. In the absence of nickel, boron was found to increase the hardness of iron; there was a maximum at 2 per cent boron, a minimum at 2.50 per cent boron, and then a renewed steady increase (to 560 Brinell) as the boron increased from 3 to 5 per cent. Nickel up to about 10 per cent increased the hardness of the iron-boron alloys. The following values are typical:

Approximate per-centage of boron	Brinell hardness number for a nickel percentage of		
	0	5	10
0.75	175	242	355
1.30	227	341	419
2.50	214	356	454
3.25	318	521	572
4.30	560	521	712

Although there is some question about the accuracy of a Brinell value of 712, there is no doubt that the alloy was very hard.

Considerable work has been done in Germany on iron-beryllium alloys and on the effect of beryllium on iron-nickel and iron-nickel-chromium alloys. Reports of some of this work have been published by Kroll.[306,387] The chief effect of beryllium is an increase in strength and hardness after age hardening. Brinell hardness tests from Kroll's first report are given in Table 116. The heat treatments were as follows:

Series	Oil quenched from		Aged at	
	°C.	°F.	°C.	°F.
A, B	1100	2010	450	840
C, D, E, F, G	950	1740	500	930

Representative tensile properties of some of the alloys are given in Table 117.

The alloys were made in lots of about 500 g. (1.1 lb.) from ingot iron, 99+ per cent nickel, 98 per cent chromium, and 95 per cent beryllium. They were deoxidized by adding about 0.3 per cent manganese or 0.2 per cent silicon. The ingots were rolled from 35 to 12-mm. (1.378 to 0.472-in.) squares.

From Tables 116 and 117 the following conclusions can be drawn: (1) About 1 per cent beryllium is necessary for the greatest increase in hardness of iron-nickel alloys, less is required if 20 per cent chromium is present; (2) in iron-nickel alloys, after aging, high hardness results from 1 per cent beryllium for all nickel contents between 4.75 and 21.8 per cent; (3) when 20 per cent

chromium is present this hardness ridge becomes a peak with 5 to 6 per cent nickel; (4) the aged alloys have high strength and low elongation; and (5) alloys of the invar type (36 per cent nickel) may be materially strengthened by adding beryllium and subjecting them to age hardening.

Kroll[387] found later that the alloys containing 12 per cent chromium, 1 per cent beryllium, and 8 to 11 per cent nickel acted abnormally in age hardening in that slow cooling from 700 to 750°C. (1290 to 1380°F.) resulted in somewhat higher hardness

TABLE 116.—BRINELL HARDNESS OF IRON-NICKEL-BERYLLIUM AND IRON-NICKEL-CHROMIUM-BERYLLIUM ALLOYS*

Series	Composition, per cent			Brinell hardness		Series	Composition, per cent			Brinell hardness	
	Ni	Cr	Be	Quenched	Aged		Ni	Cr	Be	Quenched	Aged
A	0	....	1.02	227	239	D	0	20.9	0.53	193	193
	1.59	....	1.02	273	470		1.67	20.9	0.53	206	221
	3.18	....	1.02	339	524		2.89	20.9	0.53	219	266
	4.77	....	1.02	424	611		4.17	20.9	0.53	233	269
	6.47	....	1.02	380	622†		5.16	20.9	0.53	204	285
	8.38	....	1.03	360	565		6.51	20.9	0.53	216	294†
	10.34	....	1.03	367	611						
	17.78	....	1.02	355	588	E	10.0	19.8	1.81	360	588
	21.8	....	1.02	390	588		10.0	20.3	1.55	279	424
	25.10	....	1.00	264	325		15.5	20.4	1.57	251	340
	27.65	....	1.02	185	197		7.1	20.2	1.54	358	565
							7.1	20.1	1.26	295	524
B	35.7	....	0.37	133	134		7.2	19.9	1.10	313	487
	35.6	....	0.74	169	178		7.6	20.0	1.40	312	524
	38.5	....	0.85	136	295†		7.5	20.9	1.50	385	487
	35.5	....	1.02	164	294		4.41	21.0	1.24	426	611
	35.7	....	1.48	207	216		5.39	21.0	1.24	524	636†
C	0	20.9	1.05	227	238	F	0.84	22.3	1.84	257	424
	4.13	20.9	1.06	279	588		3.26	21.0	0.79	260	505
	4.97	20.9	1.05	296	611†		4.19	21.0	0.79	267	544†
	5.40	20.9	1.06	264	494		5.19	20.5	0.77	270	478
	6.25	20.9	1.05	270	511		6.48	21.0	0.79	279	478
	7.33	20.9	1.07	286	512		7.40	20.9	0.64	251	397
	8.80	21.2	1.07	245	367						
	9.20	19.9	1.01	207	257	G	6.25	20.9	1.05	270	511
							6.25	16.5	1.05	282	477
							6.25	12.7	1.05	391	687†
							6.25	9.5	1.05	393	663
							6.25	0	1.02	380	622

* Kroll.[306]
† Peak.

than aging at 500°C. (930°F.). The hardness increase, as compared with the hardness of the quenched alloy, was 250 per cent. Alloys of the invar type containing 1 per cent beryllium also age at 700 to 750°C.

TABLE 117.—TENSILE PROPERTIES OF QUENCHED AND AGED
IRON-NICKEL-BERYLLIUM AND IRON-NICKEL-CHROMIUM-BERYLLIUM
ALLOYS*

Nominal composition, per cent			Quenching temperature		Tensile strength, lb./sq. in.	Elong-ation,† per cent	Re-duc-tion of area, per cent	Tensile strength, lb./sq. in.	Elong-ation,† per cent	Re-duc-tion of area, per cent
Ni	Cr	Be	°C.	°F.	Quenched			Quenched and aged at 500°C. (930°F.)		
7	20	1	950	1740	145,000	11	7		1	0
8	20	1	950	1740	113,700	28	68	176,200	5	8
9	20	1	950	1740	116,500	30	66	139,200	20	31
5	..	1	850	1560	185,000	7	52	258,700	3	3
15	..	1	850	1560	185,000	7	43	....	2	
36	..	1	1200	2190	83,800	27	46	159,100	5	14

* Kroll.[300]
† Gage length, $11.3\sqrt{A}$:

Although the discussion of the properties of nickel cast iron is confined to Volume II of this monograph, the investigation by Ballay[553] may be mentioned here. It shows that the presence of 1.0 to 1.5 per cent beryllium results in the age hardening of a cast iron containing 2.85 per cent total carbon, 17.35 per cent nickel, 1.56 per cent silicon, and 1.33 per cent manganese. After a suitable heat treatment the Brinell hardness of a specimen containing 1.5 per cent beryllium was 379 as compared with 172 for one containing no beryllium.

In 1932, Kroll[419] published the results of an investigation of the effect of gallium on iron and iron-nickel alloys. An iron-gallium alloy containing 1.2 per cent gallium does not age harden; if 2.9 to 14.4 per cent nickel is added and the alloy is quenched from 1100°C. (2010°F.) and aged at 500°C. (930°F.), the Brinell hardness increases 285 to 315 units.

TABLE 118.—EFFECT OF HEAT TREATMENT ON MECHANICAL PROPERTIES OF AUSTENITIC NICKEL-COPPER, NICKEL-CHROMIUM-COPPER, AND NICKEL-CHROMIUM-MANGANESE-COPPER STEELS*

Steel	Composition, per cent						Water quenched from		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Proportional limit, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent	Izod impact, ft-lb.	Grain
	C	Mn	Si	Ni	Cr	Cu	°C.	°F.							
M	0.17	0.84	0.02	28.88	.....	7.01	Hot rolled		83,400	49,500	16,000	44.0	71.3	111.2	Fine
							600	1110	83,800	48,000	28,500	45.0	71.1	118.6	Fine
							800	1470	82,000	48,500	31,000	42.5	69.3	109.1	Fine
							1000	1830	79,700	45,500	26,000	45.0	71.1	108.5	Coarse
							1200	2190	78,500	46,000	27,000	44.5	71.9	111.3	Coarse
N	0.22	1.00	0.29	12.66	13.44	2.31	Hot rolled		94,600	46,500	33,000	50.0	66.4	116.4	Fine
							600	1110	95,300	46,500	21,000	53.0	64.5	111.8	Fine
							800	1470	94,000	46,000	27,000	45.0	53.9	99.0	Fine
							1000	1830	93,500	46,000	29,000	45.0	59.9	101.5	Fine
							1200	2190	83,100	37,500	23,000	59.0	78.2	115.2	Coarse
O	0.22	5.17	0.11	6.88	14.18	2.93	Hot rolled		90,700	45,500	29,000	45.0	62.1	79.3	Fine
							600	1110	94,000	48,000	29,000	44.0	61.1	68.0	Fine
							800	1470	89,100	44,000	18,000	46.0	62.1	77.5	Fine
							1000	1830	83,500	41,000	22,000	49.0	67.7	91.0	Fine
							1200	2190	91,800	35,000	16,000	52.0	69.1	97.9	Coarse

* Pilling, unpublished data, Research Laboratory, The International Nickel Company, Inc.

203. Pilling's* Data on Mechanical Properties of Iron-nickel-copper Alloys.—The mechanical properties of three austenitic nickel steels containing copper are given in Table 118. As is apparent from these data, steel M is one of the softest austenitic steels possible to make. It coarsens at a lower temperature than other austenitic steels tested by Pilling and, in contrast to the others given in Table 118 and also in Table 95 (page 426), the

F_{IG}. 277.—The Brinell hardness of alloys of iron and Monel metal. (*Pilling, unpublished data, Research Laboratory, The International Nickel Company, Inc.*)

ductility of the coarse-grained specimens is not appreciably higher than that of the fine-grained specimens. It is remarkably insensitive to heat treatment. According to Pilling, the only marked change in any property was caused by tempering a water-quenched specimen for 24 hr. at 700°C. (1290°F.), which caused a drop in the impact value to 50 ft-lb.

Steel N is similar in composition to steel D of Table 95 (page 426) with the addition of about 2 per cent copper. The tensile properties of the two steels are much the same. The impact

* See footnote, p. 13.

resistance of steel N, however, is appreciably higher than that of steel D when the alloys are quenched from 600 and 800°C. (1110 and 1470°F.).

Like the high-nickel nickel-chromium steels A, B, and C of Table 95, steel O, containing 6.88 per cent nickel and 5 per cent manganese, has a resistance to impact that is markedly responsive to heat treatment. The impact resistance of steel N, however, after quenching from 600 and 800°C. (1110 and 1470°F.), is much higher than that of steels A, B, and C similarly treated.

The Brinell hardness of air-cooled iron-nickel-copper alloys made from ingot iron and Monel metal* is shown in Fig. 277. The maximum hardness was attained in alloys containing 10 to 25 per cent Monel metal, or 7 to 17.5 per cent nickel and 3 to 7.5 per cent copper. According to Pilling,

. . . the essential fact which Fig. 277 brings out is that the division between the austenitic and martensitic alloys is determined by the iron-nickel ratio; copper apparently acts solely as a diluent. All iron-nickel-copper alloys (carbon 0.1 per cent) in which the nickel content is less than 23 per cent of the combined iron and nickel content are martensitic (or pearlitic); all with a ratio more than 23 per cent are austenitic. The location of the austenitic boundary is subject to some displacement depending upon heat treatment, but this shift is relatively slight. . . . The maximum hardness of the air-hardening martensitic nickel-copper alloys is slightly greater than that of similar nickel steels of equally low carbon content. . . . For the particular thermal treatment these alloys received, 1 per cent Monel increases the hardness of 0.1 per cent carbon pearlitic steels 18 Brinell numbers. . . .

If more than about 0.50 per cent carbon is present in iron-nickel-copper alloys, graphitization occurs. An alloy with about 34 per cent nickel and 7 per cent copper analyzed 0.009 per cent graphite with a carbon content of 0.33 per cent; with 0.94 per cent carbon, however, the graphite was 0.49 per cent. Carbon increases the hardness from 140 Brinell for 0.10 per cent to 182 for 0.94 per cent. This increase is not so great as in the case of an austenitic nickel-chromium steel (see page 432). Iron-nickel-copper alloys do not harden so much by cold work as do the austenitic iron-nickel-chromium alloys. This is shown by comparison of the data on page 433 with the following:

* Composition: 68.14 per cent nickel, 28.73 per cent copper, 2.24 per cent iron, and 0.68 per cent carbon plus manganese plus silicon.

Reduction by cold work, per cent	Rockwell *C* hardness of alloys containing 33 per cent nickel, 6 per cent copper, and	
	0.03 per cent carbon	0.33 per cent carbon
0	−15	−8
10	+4	+7
20	6	13
30	8	15
40	10	17
50	12	19
60	14	20

The only data available on the properties of cast iron-nickel-copper steels were also supplied by Pilling. The properties of two melts containing 33 per cent nickel, 8 per cent copper, 0.9 per cent manganese, and 0.3 per cent silicon were as follows:

Property	Carbon, per cent	
	0.13	0.21
Tensile strength, lb. per sq. in.......	65,200	70,300
Yield strength, lb. per sq. in.........	39,500	44,500
Proportional limit, lb. per sq. in.....	21,500	27,000
Elongation in 2 in., per cent........	19.5	19.0
Reduction of area, per cent..........	23.6	21.3

The Brinell hardness of a step-bar casting was 151 on a ⅛-in. section and 154 on a 1-in. section. Casting properties for resistance grids, step bars, wedge bars, tensile-test blanks, and for 0.50 and 1-in. ells, tees, and couplings were satisfactory. The strength of the cast material is about 80 per cent of the strength of wrought steel of the same composition.

Castings of 17 per cent nickel, 6 per cent copper, and 3 per cent chromium steel, with 0.5 per cent carbon, were also made experimentally. The exact composition and elevated-temperature properties of this material, as determined by Wood, are given in Table 119.

204. Molybdenum in High-nickel Alloys.—Molybdenum is occasionally added to austenitic alloys which are to be used in high-temperature applications. Nickel is usually considered

TABLE 119.—EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF A
CAST STEEL CONTAINING 0.53 PER CENT CARBON, 2.84 PER CENT
SILICON, 17.3 PER CENT NICKEL, 6.25 PER CENT COPPER, AND
3.0 PER CENT CHROMIUM*

Temperature of test		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 2 in., per cent	Reduction of area, per cent
	°F.				
Room temperature		92,400	46,200	27.5	32.2
205	400	82,100	38,800	34	34.4
425	800	63,900	39,500	12.0	24.4
540	1000	53,300	37,200	7.5	19.5
650	1200	36,900	35,000	2.5	11.1

* J. T. Wood, unpublished data, Research Laboratory, The International Nickel Company, Inc.

to increase the stability of an alloy below the equicohesive temperature.   The carbide formers, especially chromium, molybdenum, and tungsten, are considered to increase the stability both below and above the equicohesive temperature because the carbide particles at the grain boundaries resist plastic flow.

As pointed out by Gregg,[415] molybdenum is added to iron-chromium and iron-nickel-chromium corrosion- and heat-resisting alloys to improve their resistance to attack by sulphuric and hydrochloric acids. It should be noted, however, that molybdenum (or silicon) tends to produce ferrite which impairs the hot-working properties and possibly the creep strength. The formation of ferrite can be avoided by increasing the nickel content.

Most of the data on the effect of molybdenum on the mechanical properties of heat- and corrosion-resistant materials were obtained on alloys used industrially for valves, containing either no nickel or much less nickel than chromium.   Except for a few values included in Tables 125 and 126, pages 483 and 485, from an investigation by Musatti and Reggiori[503] such steels are discussed in other monographs of this series.

A few data showing the effect of molybdenum on short-time elevated-temperature properties of the high-nickel heat-resistant alloys of high electric resistivity were reported by Rohn[242] and Wiberg.[368]   These are given in Table 120 together with the

properties of an iron-nickel-chromium and an iron-nickel-chromium-tungsten alloy for comparison. It is evident that the addition of either molybdenum or tungsten causes a marked increase in the tensile strength of these alloys at all temperatures between 20 and 500°C. (70 and 930°F.).

The effect of molybdenum on the hardness of iron-nickel alloys was studied by Köster[496] in connection with his investigation of phase changes in the iron-nickel-molybdenum system.

TABLE 120.—SHORT-TIME ELEVATED-TEMPERATURE PROPERTIES OF HIGH-NICKEL ALLOYS CONTAINING MOLYBDENUM AND TUNGSTEN

Investigator	Composition, per cent					Testing temperature		Tensile strength, lb./sq. in.	Yield strength, lb./sq. in.	Elongation in 100 mm., per cent	Reduction of area, per cent	Charpy impact, m-kg./sq. cm.	Estimated creep limit, lb./sq. in.*	Fatigue limit, lb./sq. in.†
	Ni	Cr	Fe	Mn	Mo	°C.	°F.							
Rohn[242]..	64	15	20	1	...	20	70	90,300	37,000	47	67	19.6		
						100	210	85,300	32,700	47	65	19.8		
						200	390	81,800	28,400	47	63	19.9		
						300	570	79,600	26,300	47	62	19.7		
						400	750	78,500	24,200	46	63	19.0		
						500	930	74,000	22,800	46	64	17.7		
	61	15	15	2	7	20	70	135,100	121,000	24	64	9.9		
						100	210	123,700	106,700	26	64	10.0		
						200	390	113,800	93,900	27	63	9.7		
						300	570	110,900	92,500	26	59	9.4		
						400	750	116,600	99,600	24	58	8.6		
						500	930	105,300	91,000	28	65	11.8		
	61	15	12	2	10‡	20	70	123,700	109,500	23	55	12.1		
						100	210	118,100	103,800	20	48	10.8		
						200	390	111,600	99,600	19	43	9.6		
						300	570	108,100	98,100	20	48	9.0		
						400	750	108,100	98,100	21	51	9.3		
						500	930	108,100	99,600	18	44	7.5		
Wiberg[368]	61	15	15	2	7	20	70	126,600	58,000§	..	..	....	......	65,400
						100	210	129,400	58,000	..	..	....	......	64,000
						200	390	129,400	56,900	..	..	....	......	62,600
						300	570	125,200	54,100	..	..	....	42,700	61,200
						400	750	119,500	48,400	..	..	....	32,700	56,900
						500	930	108,100	42,700	..	..	....	25,600	52,600
						600	1110	92,500	34,100	..	..	....	21,300	48,400
						700	1290	74,000	25,600	..	..	....	18,500	44,100

* Constant load and temperature, rate not given.
† Alternating beam.
‡ Tungsten.
§ Probably proportional limit.

Molybdenum was added to alloys having constant iron-nickel ratios of 60:40 and 20:80. Specimens were either quenched from 1200°C. (2190°F.) or identically quenched and then aged at 800°C. (1470°F.). Brinell hardness values after these treatments are shown in Table 121.

TABLE 121.—EFFECT OF MOLYBDENUM ON BRINELL HARDNESS OF IRON-NICKEL ALLOYS, QUENCHED FROM 1200°C. (2190°F.) AND AGED AT 800°C. (1470°F.)*

Molybdenum, per cent	Iron-nickel ratio, 60:40		Iron-nickel ratio, 20:80	
	Quenched	Quenched and aged	Quenched	Quenched and aged
8	120	120	120	120
15	...	...	130	140
18	160	230		
22	200	370	160	180
28	280	480		
33	320	520	200	430
40	480			
42	...	...	490	
50	530	...	525	

* Köster.[496]

205. Tungsten in High-nickel Alloys.—As mentioned in the previous section, tungsten is one of the elements which increase the stability of an alloy both above and below the equicohesive temperature; consequently it is frequently used in the heat- and corrosion-resisting alloys which must have high strength at elevated temperatures. The action of tungsten in these alloys is not clear. According to Hatfield,[277] tungsten has little or no effect on iron, iron-nickel, or iron-nickel-chromium alloys in the absence of carbon. This is also shown by the results of Jenkins and Tapsell[383] given in Table 123, page 480.

The elevated-temperature properties of the iron-nickel-chromium-tungsten alloys have been studied by a number of investigators, mostly between 1928 and 1934. A large part of this work was done by Hatfield,[277] Tapsell and Remfry,[326] Houdremont and Ehmcke,[305] Page and Partridge,[357] French, Kahlbaum, and Peterson,[338] Kahlbaum, Dowdell, and Tucker,[384] and Jenkins et al.[346,383] The work of some of these investigators

TABLE 122.—SHORT-TIME ELEVATED-TEMPERATURE PROPERTIES OF IRON-NICKEL-CHROMIUM-TUNGSTEN ALLOYS

Investigator	Composition, per cent						Prior treatment	Room temperature			800°C. (1470°F.)		
	C	Mn	Si	Ni	Cr	W		Tensile strength, lb./sq. in.	Elongation, per cent*	Reduction of area, per cent	Tensile strength, lb./sq. in.	Elongation, per cent*	Reduction of area, per cent
Hatfield[277]	0.64	0.61	1.84	13.00	14.00	1.00	Air cooled from 1000°C. (1830°F.)	126,400	22.0	31.5	27,900	52.0	67.0
	0.42	0.31	0.69	8.87	13.30	3.42	Air cooled from 950°C. (1740°F.)	127,300	7.5	....	51,000	16.0	32.8
	0.57	0.48	0.72	9.50	13.79	3.36	Forged	140,900	29.0	33.0	50,400	24.0	47.0
	0.29	1.16	1.81	24.82	14.95	2.86	Air cooled from 1050°C. (1920°F.)	106,800	35.5	50.0	43,900	24.0	51.0
	0.52	1.01	1.41	22.29	23.90	3.13	Air cooled from 1050°C. (1920°F.)	119,200	26.0	31.0	37,000	40.0	49.8
Tapsell and Remfry[338]	0.46	1.09	1.20	26.5	14.0	3.59	Forged	102,700	33.5	42.5	38,700	39.0	43.0
Houdremont and Ehmcke[395]	0.33	0.32	0.19	11.1	4.04	17.4	Not given	......	...	....	33,700		
	0.37	0.97	0.62	13.8	14.8	2.0	Not given	......	...	....	33,000	22.5	
Page and Partridge[357]	0.45	0.62	0.83	9.66	9.33	1.96	Oil quenched from 950°C. (1740°F.)	128,200	6.0	....	46,000		
	0.52	0.83	0.98	13.00	11.16	2.28	Air cooled from 800°C. (1470°F.)	......	...	....	36,800	32.7	
Kahlbaum, Dowdell, and Tucker[386]	0.53	1.58	0.96	26.00	14.80	2.93	Water quenched from 1000°C.	108,000	24.2	43.7	30,000†	29.0	53.0
	0.22	1.74	0.09	57.80	10.61	3.47	Annealed at 900°C. (1650°F.)	112,500	30.0	36.9	47,500‡	13.5	24.7
	0.21	1.73	0.09	57.60	10.70	3.33	Annealed at 900°C. (1650°F.)	110,000	31.0	51.6	46,500‡	12.5	21.2
Jenkins, Tapsell, Austin, and Rees[349]	0.55	....	....	30.35	28.85	3.96	Cast / Forged	69,400 / 148,900	2.0 / 12.0	....	45,000 / 41,000	3.5 / 45.0	

* Gage length: Hatfield, 1.25 in.; Tapsell and Remfry, and Jenkins et al., 1.5 in.; the others, 2 in.
† At 815°C. (1500°F.).
‡ At 740°C. (1360°F.).

has been summarized by Aborn and Bain,[369] Pilling and Worthington,[395] and by Gregg.[486] In addition, Strauss[365,436] has published extensive summaries of the properties of commercial heat- and corrosion-resisting alloys including those containing tungsten. Data on the precipitation hardening of alloys containing relatively large amounts of nickel and tungsten (but no chromium) have been discussed by Gregg.[486]

A tabulation of some of the data on short-time elevated-temperature properties of the heat- and corrosion-resisting alloys containing tungsten is given in Table 122.

Continuing the preliminary work by Jenkins, Tapsell, Austin, and Rees[346] (Table 122), Jenkins and Tapsell[383] investigated the effect of carbon and silicon on a chill-cast alloy containing 30 per cent nickel, 30 per cent chromium, and 4 per cent tungsten. Results are shown in Table 123. It will be noted from this tabulation that silicon has little effect on the properties, either

TABLE 123.—EFFECT OF CARBON AND SILICON ON SHORT-TIME
ELEVATED-TEMPERATURE PROPERTIES OF CHILL-CAST
IRON-NICKEL-CHROMIUM-TUNGSTEN ALLOYS*

Composition, per cent						Tensile strength, lb./sq. in.	Elongation in 1.5 in., per cent	Tensile strength, lb./sq. in.	Elongation in 1.5 in., per cent
Si	C	Ni	Cr	Fe	W	Room temperature		800°C. (1470°F.)	
0.05	0.13	29.83	29.63	36.06	3.64	61,600	24	25,000	10.0
0.04	0.65				†	62,300	20	25,800	10.0
0.03	.11				†	64,300	28	27,800	3.0
0.04	1.53				†	57,800	18	31,200	8.5
0.55	...	30.35	28.85	35.84	3.96	69,400	2	45,000	3.5
0.59	1.11				†	51,300	1	34,500	3.0
1.03	.13				†	89,800	2	54,700	2.5
0.92	1.60	29.96	28.88	34.02	3.92	79,900	3	45,200	3.0
1.54	...	29.88	29.6	35.70	3.22	99,000	1	71,300	3.5
1.43	0.62	29.74	29.7	34.72	3.55	89,600	1	62,000	5.0
1.34	1.05	30.15	28.55	35.00	3.79	108,400	2	68,500	4.5
1.59					†	95,400	2	58,600	7.0
1.5	†				Nil			53,800	3.5

* Jenkins and Tapsell.[383]

† All alloys were not analyzed completely; the nominal composition was 30 per cent nickel, 30 per cent chromium, and 4 per cent tungsten; balance iron.

at room temperature or at 800°C. (1470°F.); carbon, on the contrary, has a marked effect; alloys with 1.3 to 1.5 per cent carbon have tensile strengths between 55,000 and 71,000 lb. per sq. in. at 800°C. The elongation is high for a chill-cast alloy of this composition, varying between 3.5 and 7 per cent. With an increase in carbon to 2 per cent, the strength is much lower.

Jenkins and Tapsell found that in their long-time tests—they determined the number of days before a load of 13,500 lb. per sq. in. led to failure—the alloys containing 1.5 per cent carbon were much superior to the others. These stood up 13 to 50 days, compared with a few hours for the low-carbon alloys.

French, Kahlbaum, and Peterson[338] determined the creep stress (1 per cent flow in 10,000 hr.) for a number of alloy steels including the following:

Steel	Composition, per cent					
	C	Mn	Si	Ni	Cr	W
A	0.29	0.50	1.18	8.0	19.86	4.5
B	0.28	1.50	0.07	38.6	10.34	1.77
C	0.28	1.45	0.03	35.9	11.12	0.34

The creep stresses for these are given in Table 124. Steels *A* and *C* are included for comparison.

TABLE 124.—CREEP STRESS OF IRON-NICKEL-CHROMIUM-TUNGSTEN ALLOYS*

Steel	Prior treatment	Creep stress for 1 per cent elongation in 10,000 hr., lb. per sq. in., at				
		540°C. (1000°F.)	595°C. (1100°F.)	650°C. (1200°F.)	705°C. (1300°F.)	730°C. (1350°F.)
A	Forged	26,000	16,000	10,000	7,000	5,000
B	Rolled	26,000	13,000	4,000	1,600	500
C	Annealed at 900°C. (1650°F.)	16,000	13,000	8,500	3,500	1,000

* French, Kahlbaum, and Peterson.[338]

The same investigators also determined creep stresses for alloys containing 57 to 60 per cent nickel, 10 per cent chromium, and 3 per cent tungsten. The data on these alloys are included in the correlation of properties of the high-nickel low-iron alloys in Table 111, page 457.

Many of the high-tungsten iron-nickel-tungsten alloys are subject to age hardening. Portevin, Prétet, and Jolivet[426] have shown that the limit of solubility of tungsten in an austenitic iron-nickel alloy containing 33 per cent nickel is as follows:

Temperature		Solubility limit of tungsten, per cent
°C.	°F.	
1400	2550	23
1300	2370	17
1200	2190	13
1100	2010	12
1000	1830	11
900	1650	9.5
800	1470	8.5

After aging, the iron-nickel-tungsten alloys have excellent properties at elevated temperatures. Thus, alloys containing 25 to 40 per cent nickel and 25 to 30 per cent tungsten have a proportional limit at 800°C. (1470°F.) ranging between 46,000 and 54,000 lb. per sq. in.

206. Musatti and Reggiori's Investigation on Valve Steels.— This recent investigation on valve steels including high-nickel austenitic materials deserves considerable attention both because of its importance and because the complete results were published in a journal not widely available. Nearly 15 years ago, Johnson and Christiansen[200] published data on a number of alloy valve steels. Their conclusions were that, while an austenitic steel containing 25 per cent nickel, 17 per cent chromium, 3.5 per cent silicon, and 0.35 per cent carbon had higher strength at elevated temperatures than silchrome, cobalt-chromium, or high-speed steel, it was unsatisfactory for exhaust valves because it could not be hardened sufficiently.

Musatti and Reggiori,[503] on the contrary, recommend the use of a high nickel-chromium austenitic steel containing tungsten

TABLE 125.—COMPOSITION, HEAT TREATMENT, AND ROOM-TEMPERATURE PROPERTIES OF VALVE STEELS*

Steel No.	Composition, per cent								Prior heat treatment						Room-temperature properties					
	C	Mn	Si	Ni	Cr	W	Mo	Co	Quenching temperature °C	°F	Quenching medium	Tempering temperature °C	°F		Tensile strength, lb./sq. in.	Yield strength,† lb./sq. in.	Elongation in 100 mm., per cent	Reduction of area, per cent	Impact value,‡ m-kg./sq. cm.	Brinell hardness§
1	0.30	0.51	3.45	....	13.1	....	....	....	1025	1875	Oil	800	1470		127,300	97,400	12.8	54.2	1.05	273
3	0.46	0.49	2.89	....	11.94	4.80	....	....	1025	1875	Oil	800	1470		128,700	100,600	5.0	....	0.28	300
4	1.30	0.19	0.19	....	14.0	....	0.85	5.24	900	1650	Air	....	....		132,300	80,600	8.4	8.2	1.5	300
5	0.34	0.38	0.26	19.95	14.49	....	....	....	900	1650	Oil	....	....		107,000	....	30.8	46.3	9.2	210
6	0.64	0.27	0.31	....	4.23	20.09||	....	....	1050	1920	Oil	800	1470		135,400	92,000	2.5	3.0	1.0	307
7	0.27	0.54	2.12	7.28	19.52	4.70	....	....	900	1650	Air	....	....		132,300	74,200	27.8	38.7	5.8	273
8	0.08	0.32	0.59	8.08	20.06	....	2.49	....	900	1650	Air	....	....		104,500	61,700	32.5	25.0	4.0	225
9	1.20	0.40	0.05	....	13.50	....	1.15	1.15	900	1650	Oil	700	1290		120,200	....	11.8	18.5	0.8	265
10	0.45	1.36	1.67	27.80	14.77	4.01	....	....	900	1650	Air	....	....		116,100	78,200	21.4	38.0	4.7	230
11	0.43	1.03	0.87	14.45	12.16	1.99	....	....	900	1650	Air	....	....		123,500	81,100	27.5	40.8	6.75	250
12	0.29	1.30	Trace	33.19	11.60	....	....	....	900	1650	Air	....	....		94,600	....	19.2	55.2	12.5	190
13	0.32	1.27	1.13	31.11	12.25	3.72	....	....	900	1650	Air	....	....		103,800	49,100	30.0	46.3	8.6	195
15	0.39	0.22	0.04	10.43	4.23	20.54	0.12	....	1200	2190	Oil	850	1560		208,400	17,500	6.0	13.7	1.55	390

* Musatti and Reggiori.(603)
† Reported as elastic limit.
‡ Messnager specimen.
§ 5-mm. ball, 760-kg. load.
|| Also 1.13 per cent vanadium.

and silicon as the best material for exhaust valves.   Apparently these investigators consider high strength and ductility at elevated temperatures and high scale resistance as more important than high hot hardness.   They tested 15 alloy steels, ranging from high-speed steel and a number of high-chromium steels—plain and modified by silicon, tungsten, molybdenum, and cobalt—to iron-nickel-chromium alloys—unmodified and modified by silicon and tungsten.   The composition of 13 of these steels is given in Table 125.   The steels not included in this table were a chromium-silicon-molybdenum and a 19.5 per cent chromium, 2 per cent nickel steel, neither of which showed satisfactory properties.   In addition to the data summarized in Tables 125 and 126, Musatti and Reggiori determined arrest points and studied the structure, made corrosion tests, and determined the effect of annealing 300 hr. at 750°C. (1380°F.) on the properties.

Musatti and Reggiori summarized their results by the following tabulation:

A. Steels of excellent properties at all temperatures and to be recommended therefore for high-duty performance:

No. 7.   Disadvantage is that it tends to become brittle after long exposure at high temperature.   After 300 hr. at 750°C. (1380°F.) the average impact resistance at 800°C. (1470°F.) is lowered from 15.5 to 4.5 m-kg. per sq. cm.

No. 10.   Disadvantage is that its hardness is not very high.

No. 11.   Its corrosion resistance at 800°C. (1470°F.) is not satisfactory.

No. 13.   Disadvantage is that its hardness is low.

B. Steels of intermediate characteristics:

No. 8.   Intermediate properties, no special defects.

No. 3.   Low impact at room temperature.

No. 12.   Hardness too low.

No. 5.   Hardness too low.

C. Steels not well suited for exhaust valves:

No. 1.   Low tensile and creep strengths at elevated temperatures.

No. 4.   Low tensile and creep strengths at elevated temperatures. Low elevated-temperature corrosion resistance.   Critical point at 820°C. (1510°F.).

No. 6.   Low tensile and creep strengths and low corrosion resistance at elevated temperatures.   Critical point at 770°C. (1420°F.).

TABLE 126.—ELEVATED-TEMPERATURE PROPERTIES OF VALVE STEELS WHOSE COMPOSITION AND ROOM-TEMPERATURE PROPERTIES ARE GIVEN IN TABLE 125*

| Steel No. | Short-time properties at | | | | | | | | | | | | Repeated impact. Striking energy withstood for 400,000 blows, cm-kg. | | Creep stress, lb./sq.in., for a rate of 1 × 10⁻⁴ per cent in. per hour | | |
| | 600°C. (1110°F.) | | | | 700°C. (1290°C.) | | | | 800°C. (1470°C.) | | | | | | | | |
	Tensile strength, lb./sq.in.	Elongation in 100 mm., per cent	Reduction of area, per cent	Impact value, m-kg./sq.cm.	Tensile strength, lb./sq.in.	Elongation in 100 mm., per cent	Reduction of area, per cent	Impact value, m-kg./sq.cm.	Tensile strength, lb./sq.in.	Elongation in 100 mm., per cent	Reduction of area, per cent	Impact value, m-kg./sq.cm.	650°C. (1200°F.)	800°C. (1470°F.)	600°C. (1110°F.)	700°C. (1290°F.)	800°C. (1470°F.)
1	43,100	46.5	90.0	21.6	11,200	70.0	97.0	37.5†	6,300	95.5	98.0	34.6†	23.4	14.0	1,700	160	<140
3	55,900	35.0	67.5	6.8	16,600	49.0	89.5	9.9	8,500	72.0	92.5	18.0	24.8	11.4	4,100	2,000	900
4	66,600	19.0	43.2	4.1	34,300	38.0	67.2	4.2	13,500	78.0	74.0	5.4	21.8	11.1	1,420	700	350
5	66,000	20.5	40.5	11.3	56,900	37.2	58.5	12.0	25,300	37.2	58.5	14.1	17.9	7.6	6,000	2,100	850
6	63,600	21.2	47.3	5.6	34,100	29.0	59.5	5.4	15,500	52.3	83.0	6.7	22.7	8.7	4,000	1,100	150
7	90,500	32.0	43.3	11.4	49,400	40.0	55.5	13.8	27,700	48.7	57.0	15.5	20.5	11.3	8,250	4,100	1,150
8	76,800	15.8	15.4	6.6	50,900	23.8	39.2	5.1	31,600	43.0	48.5	5.5	19.3	7.7	9,700	2,400	800
9	......	...	...	2.7	......	...	...	2.6	....	...	...	2.7	20.3	7.9	1,900	600	350
10	82,900	20.0	35.0	8.3	63,200	23.2	42.5	7.5	32,300	36.5	64.0	6.5	...	12.4	9,700	3,600	1,700
11	......	...	...	7.8	53,800	26.0	57.8	7.0	22,000	56.5	73.5	6.8	...	14.6	11,100	3,700	1,300
12	72,500	27.5	37.0	15.6	52,300	32.6	48.5	15.0	......	...	...	16.7	19.6	7.9	6,800	2,700	1,300
13	74,800	†	‡	11.2	......	...	...	10.7		...	...	11.6	22.4	12.6	5,700	4,270	1,600
15	86,200	18.8	26.9	2.5	56,600	9.5	30.7	4.4	38,500	8.0	10.8	5.4	27.6	8.8	4,000	3,550	1,570

* Musatti and Reggiori.[503]
† Bent but did not break.
‡ Broke outside gauge marks.

No. 9. Low creep strength and very low corrosion resistance at elevated temperatures. Critical point at 780°C. (1435°F.).

No. 15. Very low corrosion resistance at elevated temperature. Critical point below 800°C. (1470°F.).

In concluding, these investigators stated:

. . . it has been shown that, as far as chemical composition is concerned, the best results have been obtained with austenitic steels containing— in addition to nickel and chromium—tungsten, which increases the strength at elevated temperature, and silicon, which increases corrosion resistance. . . . The ratio of chromium to nickel seems to be of small importance in affecting the high-temperature properties. . . . It is only noticeable that the higher the nickel, the less sensitive the steel seems to long exposure at high temperature. In group B it is difficult to draw any conclusions about the effect of composition. With a suitable addition of tungsten and molybdenum the silchrome steels are as satisfactory in their high-temperature characteristics as the austenitic nickel-chromium steels without other elements.

E. AUTHOR'S SUMMARY

1. In low-carbon iron-nickel-chromium alloys cooled at ordinary rates—in the furnace, air, or water—the sigma phase which may be present under equilibrium conditions is suppressed; hence, at atmospheric temperature these alloys consist of two phases, austenite (gamma) and ferrite (alpha). The relative amounts of these two phases depend primarily upon the composition; a structural diagram has been constructed (Fig. 274) which shows roughly the relation between composition and structure. From this diagram a rough approximation of the mechanical properties may be made. Alloys containing only austenite or ferrite are soft and tough; alloys containing a large proportion of a mixture of the two phases (martensitic constituent) are hard and strong and have relatively low elongation, reduction of area, and impact resistance.

2. Alloys containing 5 to 30 per cent nickel and variable chromium (and carbon) have properties which depend on the amount of the hard martensitic constituent present; this in turn depends upon the composition and prior treatment. With more than 20 per cent nickel the alloys are austenitic if the chromium is more than 7 per cent; they have, consequently, properties of an austenitic material, viz., tensile strengths of

85,000 to 100,000 lb. per sq. in., low proportional limit, and high elongation, reduction of area, and resistance to single-blow impact.

3. Alloys containing 30 to 40 per cent nickel and those containing about 65 per cent nickel, both with 15 to 30 per cent chromium, are widely used industrially for applications where resistance to scaling is important. Normally, they are austenitic and have the characteristic properties of austenitic materials under all conditions of heat treatment.

4. There are few data on hardness, impact resistance, and endurance limit of iron-nickel-chromium alloys at room temperature. In general, the trend of hardness is the same as the trend of tensile strength: materials which are primarily austenitic are soft; the hardness increases with the amount of martensitic constituent present. The resistance to impact of austenitic materials is high; it is low for those containing the martensitic constituent. The impact value is not always a sensitive criterion to determine if small amounts of martensite are present. The endurance limit of iron-nickel-chromium alloys is about half the tensile strength regardless of composition; these alloys, therefore, have an endurance ratio similar to other ferrous materials.

5. Because of differences in testing technique and other factors, the elevated-temperature properties of iron-nickel-chromium alloys are valid only for the specific alloy and testing conditions used. The data indicate, however, that most austenitic iron-nickel-chromium materials, have a tensile strength of approximately 25,000 lb. per sq. in. at 870°C. (1600°F.). Cast alloys have approximately the same strength as wrought alloys at 760°C. (1400°F.) and above, but the ductility of the cast material is lower at all temperatures. From the few data available it seems likely that the iron-nickel-chromium alloys have approximately the same endurance ratio (0.50 ± 0.05) at elevated temperatures as they have at room temperature.

6. Although the determination of creep is attended with much difficulty, with the result that the data obtained may be of questionable value, enough has been done to show that iron-nickel-chromium alloys have a creep strength at 540 to 650°C. (1000 to 1200°F.) which is some 5 to 10 times the creep strength of carbon steel. It is also much higher than the creep strength of iron-chromium alloys. Data are given which indicate that

15 to 25 per cent nickel doubles the creep strength of a low-carbon alloy containing 10 to 15 per cent chromium.   This is true for both wrought and cast materials.

7. Pilling and Worthington[395] summarized the effect of nickel on the high-temperature properties of wrought alloys containing 20 per cent chromium, using previously published data and their

Fig. 278.—Effect of nickel on the strength properties at 650°C. (1200°F.) of iron-nickel-chromium alloys containing 20 per cent chromium.   (*Pilling and Worthington.*[395])

own work.   Results of short-time tests, creep-stress determinations for a rate of 1 per cent in 10,000 hr., and the stress which causes failure in 10 days, all at 650°C. (1200°F.), are plotted in Fig. 278.   Available data on the effect of elevated temperatures on modulus of elasticity, hardness, and impact resistance are summarized in section 196.

8. Alloys consisting of approximately 65 per cent nickel, 13 to 20 per cent chromium, remainder iron have short-time tensile

strengths varying between 9000 and 16,000 lb. per sq. in. at 1000°C. (1830°F.). The elongation and reduction of area of cast materials of this class are low at all temperatures, even at 1000°C. These alloys, usually with about 3 per cent tungsten added, have creep strengths which compare favorably with the 26 per cent nickel plus chromium alloy.

9. The effect of a large number of alloying elements, such as manganese, copper, silicon, tungsten, molybdenum, cobalt, titanium, boron, beryllium, and others, on the mechanical properties of iron-nickel and iron-nickel-chromium alloys has been studied. Some of these elements have been used to strengthen the austenite, especially at elevated temperatures; others have been used to increase hardness and strength by precipitation; still others have been used to insure that the marginal alloys which may be partly martensitic after certain treatments will be austenitic under all conditions.

10. Manganese favors strongly the retention of austenite in iron-nickel alloys, but the carbon must be low to insure satisfactory hot- and cold-working properties. Adding manganese in quantity to marginal austenitic alloys containing nickel and copper permits a progressive increase in iron content and a decrease in total alloys without the formation of martensite after air hardening. Manganese is about 1.9 times as effective as nickel in retaining austenite.

11. Binary austenitic iron-nickel alloys can be precipitation hardened by adding titanium and subjecting them to a suitable treatment. If the titanium is too high, trouble is encountered in forging. The optimum titanium content for alloys containing 30 to 50 per cent nickel is 2.2 to 3.0 per cent. The hardness of such alloys can be increased from 150 to about 320 by heat treatment. Iron-titanium alloys also age harden if nickel is added.

12. Austenitic alloys of iron, nickel, and manganese and of iron, nickel, and cobalt can be precipitation hardened by titanium. With proper heat treatment, proportional limits of 50,000 to 70,000 lb. per sq. in. can be obtained with good ductility. Austenitic alloys of iron, nickel, and chromium can also be precipitation hardened by titanium. Data are quoted which show that after proper heat treatment a tensile strength of 130,000 lb. per sq. in., a proportional limit of 65,000 lb. per sq. in., an elongation

of 38 per cent in 2 in., a reduction of area of 62 per cent, and an Izod impact resistance of 80 ft-lb. can be obtained.

13. Boron increases the hardness of iron; if nickel is added to iron-boron alloys, the hardness is increased still more. The addition of beryllium and gallium to iron-nickel or iron-nickel-chromium alloys makes age hardening possible. Alloys containing 5 to 20 per cent nickel and 1 per cent beryllium are hard and relatively brittle; a tensile strength of about 250,000 lb. per sq. in. and an elongation of 2 per cent can be obtained.

14. Austenitic iron-nickel-copper alloys have, in general, the properties of other austenitic high-nickel alloys. Some are remarkably insensitive to heat treatment. The division between austenitic and martensitic alloys is determined by the iron-nickel ratio; copper apparently acts solely as a diluent. If more than 0.40 to 0.50 per cent carbon is present, graphitization occurs. Data are given which indicate that iron-nickel-copper alloys are not hardened so much by cold work as are the iron-nickel-chromium alloys.

15. Molybdenum or tungsten is frequently added to iron-nickel-chromium alloys to increase scale resistance, corrosion resistance, and stability at elevated temperatures. Molybdenum or tungsten increases the tensile strength of the 65 per cent nickel, 15 per cent chromium, 15 per cent iron material at temperatures of around 500°C. (930°F.). The elevated-temperature tensile strength of alloys containing about 35 per cent nickel and 20 per cent chromium is greatly increased by increasing the carbon. As this results in a reduction in ductility, the upper limit for carbon in the industrial alloys is 0.9 per cent. Available data on the creep strength of iron-nickel-chromium-tungsten alloys are summarized.

CHAPTER XIII

CORROSION

Corrosion of Iron-nickel Alloys—Corrosion of Iron-nickel-chromium Alloys—Scaling—Author's Summary

Winning the ordinary metals from their ores is only half the battle, for there is another half consisting of the attempt to restrain them from returning to their "dust." The problem is obscure and complicated. So far as iron is concerned, it would be futile to attempt to revise Cleaves and Thompson's[520] ultimately terse statement that "iron rusts." Alloys of iron rust also. In the widest sense, metallurgy has been relatively powerless in the battle; it is only for some special purposes, for which cost is an indecisive factor, and for definitely restricted conditions of exposure, that special alloys can be used. The universal resistant is about as remote as the universal solvent.

Progress has been made in establishing a science of corrosion, but to date its structure contains a number of flimsy members. The more or less well-established facts of corrosion are discussed at length in the treatises of Evans,[595] McKay and Worthington,[570] and Speller.[544] McKay and Worthington have stated the case so well that some of their introductory remarks can be paraphrased advantageously.

Until recently it was often considered that a given metal in a given solution corrodes at a rate of more or less absolute value. It is now known that many details of exposure must be known if wide and proper interpretation of results is to be made; for example, impurities in the solution may have to be considered. Other important factors are the degree of aeration of the solution, the temperature, the relative motion, the initial surface condition of the metal, and reproducibility. It is desirable also to know the degree of control of such factors during the test. Most tests are made without sufficient control, but even so results of such tests are not necessarily valueless. If a corrosion rate of 37.5 mg. per sq. dm. per day is obtained by simple immer-

sion in a beaker, it may be concluded that the expected rate perhaps lies between 25 and 50 mg. per sq. dm. per day for total immersion of the specimen in a quiet, unaerated solution.   This information is useful, for it means that the rate is greater than 1 but less than 100 mg. per sq. dm. per day.   Under service conditions, however, other factors may be operative that upset literal interpretation of such a rate datum.   McKay and Worthington gave the following example:

It is desired to know whether copper or 18-8 stainless steel would be better as a construction material for a tank to hold a quiet acid solution. It is found in a quiet beaker test, the specimens being totally submerged, that the rate for copper is 10 mg. per sq. dm. per day and that for 18-8 less than 1 mg. per sq. dm. per day.   Both rates are low and consistent with long life.   Since a copper tank of the type desired is cheaper, such a tank is installed.   Much to the dismay of those responsible, the tank suffers premature failure at the solution level, the rate of penetration being about 25 times more rapid than calculated from the results of the beaker test.   Presumably the tank should have been made of 18-8, and therefore a new 18-8 tank is installed.   *Mirabile dictu*, this tank fails at the bottom by isolated pitting, in even more rapid time than the copper.

The beaker test had indicated truly enough the behavior of the two metals in quiet, partially aerated submersion.   The unexpectedly rapid corrosion of the copper was due to the fact that the acid at the solution level was much more highly aerated than that against the copper specimen, plus the fact that corrosion products built up on the metal at the solution level, and these led to accelerated concentration cell attack. The pitting of the 18-8 on the other hand developed through local insufficiency of aeration and consequent failure of the protective film to be maintained.

It follows, therefore, that a single set of comparative corrosion rates may lead to misinterpretation; factors operative under the conditions of service must be considered.

The practical significance of the rates of corrosion cited may be indicated roughly as follows: 0 mg. per sq. dm. per day represents roughly the lower limit of measurement and, therefore, no observable corrosion; from 1 to 10 represents very slight corrosion; from 10 to 100 represents rates no longer negligible, and those near 100 may be serious; from 100 to 500 represents rates that are serious; and rates greater than 500 usually indicate

failure. Another unit of rate of corrosion is penetration in inches per year; it is related to milligrams per square decimeter per day as follows:

$$\text{mg. per sq. dm. per day} \times \frac{0.001437}{\text{density}} = \text{in. per year}$$

For example, a loss of 100 mg. per sq. dm. per day for an alloy containing 60 per cent nickel, 15 per cent chromium, and 25 per cent iron is equivalent to a penetration of 0.018 in. per year.

In this chapter, arbitrary distinction is drawn between corrosion at ordinary temperatures, no matter what the attacking agent may be, and that at elevated temperatures, which is well known as oxidation and scaling. On the whole, knowledge of the behavior of metals under high-temperature attack is on surer footing than that of corrosion at ordinary temperatures. This perhaps means that the factors are fewer or less subtle.

For example, the investigator of scaling resistance is unlikely to be troubled by localized attacks stimulated by barnacles—which are not averse to attaching themselves to specimens immersed in sea water under natural conditions. Even so, the behavior of some alloys at elevated temperatures is such that the necessity of practical judgment has not been displaced by generalizations.

Attention in this chapter is necessarily centered on iron-nickel alloys and on those alloys in which nickel is the major addition element. This obscures the relation of these alloys to their close neighbors, consequently slight encroachment on the field of "The Alloys of Iron and Chromium" is necessary in several instances.

No attempt is made to include a summary of every statement that has been made on the corrosion of iron-nickel alloys, although all that could be located were examined. It is felt that an exhaustive summary could serve no purpose whatever. For example, many of the early investigators of nickel steel were impressed by the fact that fractured specimens showed less tendency to tarnish than the ordinary steels. Then again, in later years, during the rapid development of "stainless" steels. it became almost inevitable that an iron-nickel alloy or two would be included in each series of tests. Such isolated specimens, usually tested under varying to unknown conditions, yielded results of doubtful significance. The literature selected for

review here, therefore, is intended merely to give as consistent a picture as seems possible at present; it must be admitted, however, that the result is far from satisfying. But iron-nickel alloys are hardly unique in this respect.

A. CORROSION OF IRON-NICKEL ALLOYS

Certain gamma-phase alloys of iron and nickel are used for their special properties, such as low thermal expansion or high magnetic permeability. All have greater resistance to corrosion than ordinary iron and steel, but they are seldom if ever used for this reason alone. More resistant materials are known (many contain combinations of nickel and chromium), consequently the corrosion properties of the binary alloys are not very important. This fact is reflected by the relative scantiness of published information. It is fortunate that the special-purpose alloys have the greater resistance to corrosion, but they would be used just as much without it.

There is sufficient information on iron-nickel-chromium alloys to demand separate review. Otherwise the brief discussion of complex alloys containing iron and nickel is confined to this portion of the chapter.

207. Atmospheric Corrosion of Iron-nickel Alloys.—Nickel increases the resistance of iron to attack by the atmosphere, but not to the extent found for certain other alloys. According to Pilling,* two types can be recognized; *viz.*, "rusting" and "non-rusting" alloys. In a series of tests, the distinction was especially noticeable after the first few weeks of exposure (to an industrial atmosphere). The rusting alloys were covered with the familiar yellowish-brown powdery rust, whereas the non-rusting alloys were covered with a thin semi-transparent film that was yellow, green, or purplish in color. After several years of exposure, the color difference was not evident; the coatings were thick and dark and contained atmospheric solids such as dust and soot as well as the products of corrosion. The distinction could be made by scratching, however; the resulting powder was reddish brown for the rusting alloys and light olive for the non-rusting alloys.

Some of the iron-nickel alloys were unusual in that the rust coating could be separated easily from the metallic base. In the alloys with the higher iron content the surface thus exposed was

* See footnote, p. 13.

not metallic but colored, such as yellow or green. The rust coating on 50 and 60 per cent nickel alloys flaked off easily and exposed a bright metallic surface. Further discussion appears in connection with iron-nickel-copper alloys.

The increased resistance to atmospheric attack of iron-nickel alloys, as compared with iron, is of practical usefulness, of course. For example, alloys containing 36 and 42 per cent nickel

FIG. 279.—The corrosion of iron-nickel alloys by hydrochloric acid.

are often used for surveyor's tapes; their resistance to attack by the atmosphere, rain, and salt water makes it easier to keep the tapes in a serviceable condition. According to Sands,[431] it is important to prevent the beginning of attack, because, once begun, discoloration may spread rapidly over the surface of the alloy.

208. Corrosion of Iron-nickel Alloys by Hydrochloric Acid.— According to data of Pilling and Ackerman,[316] nickel content

has little effect on corrosion by 5 per cent hydrochloric acid; this is shown by Fig. 279. Greater variation was found by Utida and Saitô[224] for 10 per cent acid, and by Schmidt and Wetternik.[610]

209. Corrosion of Iron-nickel Alloys by Nitric Acid.—Data on corrosion by nitric acid are summarized in Fig. 280. Those of

FIG. 280.—The corrosion of iron-nickel alloys by nitric acid.

Pilling and Ackerman[316] for 5 per cent acid and those of Utida and Saitô[224] for 10 per cent acid agree more or less in trend; both sets of points show decreased loss with increased nickel content, especially in the gamma-phase range. Weight-loss values of Pilling and Ackerman indicate that nickel is about 100 times more resistant than iron to 5 per cent nitric acid, but even so its loss is heavy.

210. Corrosion of Iron-nickel Alloys by Sulphuric Acid.—Solutions of sulphuric acid have been used for many years to test the corrosion behavior of iron-nickel alloys. Hadfield[31] in 1899, for example, reported tests made to disprove the seemingly prevalent belief of that time that the high-nickel steels were of great resistance to corrosion. Alloys containing up to 50 per cent nickel were immersed in 50 per cent sulphuric acid for 21 days;

FIG. 281.—The corrosion of iron-nickel alloys by sulphuric acid.

it was found that all lost weight. The first extensive series of alloys was tested by Burgess and Aston[98] who immersed their specimens in 20 per cent sulphuric acid for 1 hr. A marked reduction of weight loss per unit area with increased nickel content was found. For example, a sample of electrolytic iron lost 0.013 g. per sq. cm., whereas a 75 per cent nickel alloy lost 0.00049 g. per sq. cm. It seems sufficient, however, to confine most attention to the results of Utida and Saitô,[224] Endo,[273] Pilling and Ackerman,[316] Fritz as reported by Fry,[446] and to those of Fink and DeCroly.[300] Some results of all are compared

in Fig. 281. Excepting the alloys of Endo, which contained about 0.5 per cent carbon, nearly all contained less than 0.1 per cent carbon. Also, excepting Fritz's results, which are for a temperature of 50 to 60°C. (120 to 140°F.), and those of Pilling and Ackerman, which are for a temperature of 30°C. (85°F.),

FIG. 282.—The influence of concentration on the corrosion of iron-nickel alloys by sulphuric acid.   (*Fink and DeCroly.*[300])

all are for room temperature. Considering the nature of such tests, there is surprising agreement among the Japanese and German data. (For the sake of comparison, all results were converted to terms of average loss per hour. Utida and Saitô's tests ran 24 hr., as did those of Fink and DeCroly; Endo's, 5 hr.; and Fritz's evidently 1 hr.) They show decreased loss with increased nickel content up to about 35 per cent nickel and

thereafter little change. Losses found by Fink and DeCroly were considerably greater; this may be due to the fact that their test method was intermittent. Immersion times were usually 48 and 96 hr. (total time 96 and 168 hr.). The tests were usually conducted at room temperature. Four samples of each alloy were used and results were reproducible within 10 per cent, excepting a few cases of heavy pitting or very low loss values. Figure 282 summarizes the results for acid concentrations of 5 to 96 per cent. For 5 and 10 per cent sulphuric acid solutions, corrosion decreased more or less regularly with increased nickel content. Higher acid concentrations resulted in a minimum rate of corrosion in the vicinity of 50 per cent nickel.

The losses found by Pilling and Ackerman indicate little change with composition once a nickel content of about 25 per cent is exceeded. In magnitude, however, they are greater than those of Fritz and of Utida and Saitô by a factor of 10. This is perhaps due to the fact that the acid solutions of Pilling and Ackerman were both aerated and agitated. It has long been recognized that environmental factors are very important in corrosion testing, so it may be that the three groups of more or less self-consistent data shown in Fig. 281 are fairly representative for results to be obtained under the specific conditions of test used.

211. Corrosion of Iron-nickel Alloys by Saline Solutions.—As early as 1900, Howe[37] reported that the rate of corrosion of a 26 per cent nickel iron-nickel alloy was about one-third that of wrought iron in sea water as well as in the atmosphere. Similar results were found by Diegel[49] for alloys containing 6 and 30 per cent nickel. Results of the most extensive investigations of marine corrosion have appeared in a series of reports, of which the two recent ones by Friend[413,484] may be cited. The first is for specimens exposed 3 years at approximately half-tide level under a jetty at Southampton. At the end of the exposure the bars had collected a layer of mud and oil and a miscellaneous assortment of shell fauna. The shell fauna seemingly had no effect on corrosion while living, but when dead it stimulated local attack. Iron-chromium-nickel alloys (15 to 20 per cent chromium and 2 to 10 per cent nickel) and nickel had high resistance to general corrosion, but could not resist local attack by defunct fauna. The addition of iron to nickel, judging from results on alloys containing 78 and 36.7 per cent nickel, greatly increased

TABLE 127.—MARINE CORROSION OF SOME ALLOYS EXPOSED 10 YEARS AT COLOMBO, CEYLON*

Material	Weight loss, mg. per sq. dm. per day			Appearance		
	Atmosphere	Alternate wet and dry	Total immersion	Atmosphere	Alternate wet and dry	Total immersion
Ingot iron..................	75	30	17	Perforated; edges corroded	Uniformly corroded	Generally uniform corrosion; a few pits
Low-carbon steel.............	61	31	22	Uniformly corroded	Severely corroded and pitted; one perforation	Pitted
0.6 per cent copper steel.........	61	31	17	Uniformly corroded	Deeply pitted	Areas of original surface; pitted
13.6 per cent chromium steel.....	4.4	17	12	Faintly pocked	Serious local corrosion	Local corrosion
3.75 per cent nickel steel.........	61	31	17	Uniformly corroded	Pitted; two perforations	Areas of original surface; pitted
36.5 per cent nickel iron–nickel alloy	0.7	7	8	Excellent	Best; areas of original surface	Best; local corrosion

* Friend.[484]

corrosion. This was found also by Stepanow, Marschak, Bala-schowa, and Kabanowa[545] in tests of electrolytically deposited alloys. Data given in the other report by Friend, however, indicate that certain of the iron-nickel alloys may have sufficient resistance to marine corrosion to be useful. Specimens of several grades of iron, carbon steels, copper steels, a chromium steel, a nickel steel, and a gamma-phase iron-nickel alloy were exposed 10 years under several conditions at Plymouth, England, and at Colombo, Ceylon. Some of the results at Colombo, where corrosion was greatest, are given in Table 127. Of the materials tested, the 36.5 per cent nickel alloy clearly had the greatest resistance to corrosion for all conditions of exposure.

Increased resistance to attack by sodium chloride solutions by the addition of nickel to iron was found in laboratory tests by Fink and DeCroly.[300] Specimens were alternately immersed in a 5 per cent solution of the salt. The rate of corrosion of 48 and 80 per cent nickel alloys was about one-fifteenth that of iron.

212. Corrosion of Iron-nickel-silicon Alloys.—A few years ago alloys containing nickel and silicon, with or without chromium, were proposed as materials resistant to sulphuric acid. The composition of one was 25 per cent nickel and 5 per cent silicon according to Earnshaw.[296] Schenck[320] recommended alloys containing 15 to 35 per cent nickel and 5 per cent silicon for the handling of sulphates and nicotine as well. According to Woldman and Dornblatt,[535] however, these alloys have been "discontinued."

213. Corrosion of Iron-nickel-molybdenum Alloys.—An alloy consisting essentially of 20 per cent each of iron and molybdenum and the remainder nickel, described by Field,[299] has high resistance to attack by hydrochloric acid. For 37 per cent acid at room temperature, a weight loss of 2.5 mg. per sq. dm. per day is quoted; this is equivalent to a penetration of 0.00036 in. per year. For aerated 10 to 37 per cent acid at 70°C. (160°F.), weight loss was 120 to 200 mg. per sq. dm. per day. Losses of the same order of magnitude were found for 10 to 77 per cent sulphuric acid and 10 to 85 per cent formic acid. The material does not resist oxidizing agents such as nitric acid, wet chlorine, and certain salts, but is not attacked by solutions of strong alkalis. According to Everhart,[412] an alloy containing 35 per cent nickel, 25 per cent chromium, and 5 per cent molybdenum has a satis-

factory resistance to lime and electrolytic caustic soda. The corrosion of alloys containing 28, 35, and 60 per cent nickel and up to 20 per cent molybdenum was investigated by Schmidt and Wetternik.[610]   The addition of 2 per cent molybdenum increased resistance to boiling hydrochloric acid solutions, but further increase of molybdenum content effected little change. The greatest resistance found was for the 60 per cent nickel, 20.6 per cent molybdenum alloy; the corrosion rate in boiling 4 per cent acid was 900 mg. per sq. dm. per day and that in 8 per cent acid was 1380 mg. per sq. dm. per day. The initial effect of molybdenum addition upon exposure to boiling 30 per cent sulphuric acid was to decrease rapidly the resistance to attack; relatively large additions of molybdenum increased resistance. The most resistant alloy again contained 60 per cent nickel and 20.6 per cent molybdenum; the rate of corrosion was 120 mg. per sq. dm. per day.   By adding about 2.5 per cent copper as well as molybdenum the composition range of increased corrosion by sulphuric acid was obliterated.   For the 60 per cent nickel series, the rate of corrosion was about 50 mg. per sq. dm. per day for all molybdenum contents, and not much greater for the 28 and 35 per cent nickel series.   Corrosion rates in boiling hydrochloric acid solutions remained on the order of thousands of milligrams per square decimeter per day, however.

214. Corrosion of Iron-nickel-copper Alloys.—On page 494 it is stated that Pilling was able to classify alloys into rusting and non-rusting types.   His data on iron-nickel-copper alloys, so classified, are shown in Fig. 283.   The curves are roughly located boundaries of fields of like corrosion behavior; the heavy curve is the boundary between fields of rusting and non-rusting alloys. The material showing the greatest corrosion was remelted ingot iron.   As is stated elsewhere, nickel increases the resistance of iron to atmospheric corrosion.   Pilling found, however, that the simultaneous addition of nickel and copper increased the resistance more rapidly, and alloys containing more than 40 per cent nickel plus copper in the 70:30 ratio were definitely of the non-rusting type.   Increase of the relative copper content decreased corrosion resistance, possibly because of the presence of an iron-rich phase.   Figure 283 indicates that the most effective nickel-copper ratio may be 80:20, but there are not enough data to decide the point.

Other tests* showed that the boundary between the fields of rusting and non-rusting alloys depends upon the nature of the

FIG. 283.—Types of rust coating formed on iron-nickel-copper alloys upon exposure to the atmosphere. (*Pilling, unpublished data, Research Laboratory, The International Nickel Company, Inc.*)

FIG. 284.—Effect of natural atmospheres on the rusting limits of iron-nickel-copper alloys. (*Pilling, unpublished data, Research Laboratory, The International Nickel Company, Inc.*)

atmosphere (Fig. 284, for which the atmospheres were rated as follows: Tucker's Island, clean marine; Huntington, clean inland; Bayonne, mild industrial; Pittsburgh, severe industrial). It

* See footnote, p. 13.

appears that the more severely "industrial" the atmosphere, the greater is the iron content—for a given nickel-copper ratio—of the boundary between the fields of rusting and non-rusting alloys. The sulphur content of the air is probably the determining factor. The *amount* of corrosion, however, increases with the severity of the atmosphere, and the amount is certainly more important than the kind of coating.

According to recent data quoted by Pilling (in discussion of a paper by Cone[555]), low-carbon nickel-copper steels of the low-alloy type have greater resistance to marine and sulphurous industrial atmospheres than the corresponding alloys without nickel.

The acid corrosion of iron-nickel-copper alloys was investigated by Schmidt and Wetternik.[610] Copper up to 5 per cent increased somewhat the resistance of 28, 35, and 60 per cent nickel alloys to boiling 4 and 8 per cent hydrochloric acid but had little effect on corrosion by 30 per cent sulphuric acid.

215. Corrosion of Iron-nickel-copper-silicon Alloys and Effect of Additions of Chromium or Molybdenum.—The corrosion of a large number of commercial alloys by 10 per cent sulphuric acid solution was determined by Miller.[423] Ground and polished specimens were immersed in flasks equipped with reflux condensers, after which the solution was raised to the boiling temperature; the boiling was continued 24 hr. Alloy compositions and the corrosion rates are given in Table 128. Alloy *A*, which contained no nickel, and alloys *B*, *E*, *K*, and *F*, in which chromium exceeded nickel in content, were readily attacked. The resistance of alloys containing more nickel than chromium was high, on the other hand (for example, alloys *AA*, *BB*, *CC*, *DD*, and *EE*). These data indicate also that relatively small amounts of silicon, copper, tungsten, and molybdenum increase the resistance of complex alloys. The alloys having the greatest resistance, such as *T* and *U*, were non-ferrous; they are included for comparison.

Tests of laboratory alloys containing 2 per cent silicon, 1 per cent copper, up to 30 per cent nickel, and up to 12 per cent molybdenum in 10 per cent sulphuric acid at room temperature led to the exclusion of molybdenum, because, for all samples, the rate of corrosion was increased by increased molybdenum content. Additional alloys were therefore prepared, containing

TABLE 128.—CORROSION OF SOME ALLOYS IN BOILING 10 PER CENT
SULPHURIC ACID SOLUTION*

Mark	Composition, per cent								Weight loss, mg./sq. dm. per day
	C	Mn	Si	Cu	Mo	W	Cr	Ni	
A	0.26	0.34	0.79	....	.....	...	27.06	....	878,000
GG	0.18	0.37	0.18	....	.....	...	.....	30.6	4,460
B	0.08	0.29	0.44	....	.....	...	17.38	8.39	45,200
E	....	....	.....	....	.....	...	18	8	42,200
K	....	....	.....	....	.....	...	30	9	93,200
F	....	....	.....	....	.....	...	21	12	41,200
W	....	....	.....	....	.....	...	15	35	5,000
L	....	....	.....	....	.....	...	15	35	1,200
V	0.18	....	.....	....	.....	...	12	60	820
C	0.40	0.62	1.15	....	.....	...	7.5	19.5	7,000
D	0.20	0.62	1.10	....	.....	...	7.5	19.5	6,340
AA	0.04	....	1.94	....	.....	...	20.64	23	360
BB	0.17	....	1.98	....	.....	...	19.30	22.97	410
CC	0.24	....	2.84	....	.....	...	22.51	22.51	340
DD	0.33	....	2.44	....	.....	...	20.55	21.79	330
EE	....	....	4.29	....	.....	...	11.52	36.99	360
O	0.25	....	2.75	1.25	.....	...	11	16	2,360
M	0.25	....	3.25	1.10	1.10	...	19.25	22.5	210
J	0.15	....	0.35	....	1.5	...	19	9	1,870
G	0.40	....	.....	....	.....	3.5	14	26	730
H	0.30	....	.....	....	.....	2.5	11	60	450
R	....	2	.....	....	20	....	.....	58	760
S	....	....	.....	....	17	5	14	58	340
T†	....	....	10	3	.....	...	.....	85	15
U	....	....	.....	8	.....	...	25	60	0
P	0.85	0.65	14.5	....	.....	...	.....	....	1,360

* Miller.[423]

† 1.5 per cent aluminum.

3 to 4 per cent silicon, up to 20 per cent copper, and 5 to 40 per
cent nickel. Chromium was added to some as well. Results
showed that the rate of corrosion was decreased steadily as
copper content was increased to 12.5 per cent; it was increased
by increasing the copper content to 20 per cent. Nickel up to
30 per cent decreased corrosion; a slight increase was observed at
35 and 40 per cent nickel. A silicon content of 3 per cent was
found best, and chromium up to nearly 20 per cent increased the
rate of corrosion, although a marked decrease occurred at 20 per

cent chromium.   Results for a few of the 84 laboratory alloys
are reproduced in Table 129.   The sharp drop of corrosion rate
between 10 and 20 per cent nickel is noteworthy, as is the
relatively good resistance of the relatively cheap—though
unforgeable—alloy containing 25 per cent nickel, 12.5 per cent
copper, and 3 per cent silicon.

TABLE 129.—CORROSION OF SOME LABORATORY ALLOYS IN UNAERATED,
BOILING, 10 PER CENT SULPHURIC ACID*

Alloy	Composition, per cent			Weight loss, mg. per sq. dm. per day	Remarks
	Ni	Cu	Si		
36	5	....	3	283,000	
37	10	....	3	178,500	
38	20	....	3	15,800	
39	30	....	3	6,000	
40	40	....	3	7,100	
43	30	3	3	1,650	Most resistant forgeable alloy
61	25	12.5	3	420	Most resistant non-forgeable alloy

* Miller.[423]

B. CORROSION OF IRON-NICKEL-CHROMIUM ALLOYS

Iron-nickel-chromium alloys are seemingly the most versatile
of the non-precious metals used at present for their resistance to
corrosion.   They fall within several well-defined groups on the
basis of composition:

18 per cent chromium, 8 per cent nickel.
(12 to 18 per cent chromium).
12 to 20 per cent chromium, 60 to 80 per cent nickel.
15 per cent chromium, 35 per cent nickel.
30 per cent chromium, 15 per cent nickel.
(28 per cent chromium).

The remainder is chiefly iron in all groups.   Most information on
corrosion by such agents as the atmosphere, sea water, and
liquids such as acid and salt solutions is on alloys of the first two
groups; it is therefore properly discussed in "The Alloys of Iron
and Chromium."   However, to orient properly the information
on alloys containing more nickel than chromium a brief over-
lapping is necessary.

Iron-chromium alloys have high resistance to rusting if the chromium content is 12 per cent or more. Nickel is added for two purposes: (1) to produce gamma-phase alloys, since their mechanical properties are more useful for certain purposes than those of the high-chromium alpha-phase alloys; (2) to take advantage of special corrosion behavior contributed by nickel.

Iron-nickel-chromium alloys are characterized by the fact that they have high resistance to oxidizing solutions. Their resistance to oxidation depends upon interaction with oxidizing agents, which results in the formation of an oxide film.

Nickel is less chemically reactive than either chromium or iron, consequently, according to LaQue,* nickel in iron-nickel-chromium alloys should increase resistance to corrosion under conditions of exposure such that the "passivating effect of chromium alone would not be sufficient to provide resistance to corrosion." In addition, nickel itself is capable of developing passivity, both in elemental form and in alloys; it tends, therefore, to increase the range of conditions under which the alloys remain passive. Still other additions, such as molybdenum, copper, and silicon, may act in the same way.

The degree of passivity of nickel-base chromium alloys is less than that of iron-base alloys of similar chromium content, but this is advantageous in some instances, since there is less tendency toward sharp changes of behavior, or for intense local attack as a consequence of breakdown of the protective film.

The 18 per cent chromium, 8 per cent nickel alloys are supposed to combine satisfactory general resistance to corrosion with the most useful mechanical properties. Among the instances in which the higher nickel alloys are more satisfactory, McKay and Worthington[570] cited neutral chloride solutions and acid solutions of low oxidizing power. They stated that the 80 per cent nickel, 14 per cent chromium alloy is more resistant than the 18 per cent chromium, 8 per cent nickel alloy when the two are in the same state of activity. For example, in hydrogen-saturated 5 per cent sulphuric acid solution, the former lost 68 mg. per sq. dm. per day, as compared with a loss of 440 mg. per sq. dm. per day for the latter. For another example, sodium chloride solutions have been known to cause deep, progressive

* Private communication.

pitting in the latter, whereas under the same conditions, pits
in the former were shallow and not progressive.

216. Atmospheric Corrosion of Iron-nickel-chromium Alloys.
Tests of a few iron-nickel-chromium alloys conducted by Pilling*

Fig. 285.—Effect of natural atmospheres on the rusting limits of iron-nickel-chromium alloys. (*Pilling, unpublished data, Research Laboratory, The International Nickel Company, Inc.*)

indicated that the type of atmosphere is important in deter-
mining the minimum permissible chromium content.   The data
of Fig. 285 indicate that a minimum of 10 per cent is permissible

Fig. 286.—Effect of nickel and chromium on the type of rust coating formed upon an exposure for 2 years at Bayonne. (*Pilling, unpublished data, Research Laboratory, The International Nickel Company, Inc.*)

only in the practical absence of sulphurous gases and salt water.
Alloys containing more than 10 per cent chromium remained
untarnished in a clean inland atmosphere, but those containing

* See footnote, p. 13.

18 per cent chromium rusted in industrial and marine atmospheres. Figure 286 shows the way in which the type of coating varies with composition. Increased nickel content clearly decreases the chromium content required for the production of a smooth, adherent coating.

217. Corrosion of Iron-nickel-chromium Alloys by Nitric Acid. Additions of nickel to iron-chromium alloys are relatively unimportant so far as resisting nitric acid is concerned. According to data of Guertler and Ackermann[274] and of Pilling and Ackerman,[316] chromium content is the decisive factor. McKay and Worthington[570] stated that typical losses are 10 mg. per sq. dm. per day or less for acids of more than 20 per cent concentration. Corrosion is ordinarily greater in solutions of lower concentration, but even these can be handled successfully by increasing the chromium content to 20 per cent or more.

Probably the largest number of alloys tested (in 5 and 35 per cent acid) were those of Pilling and Ackerman. In general, losses were greater than those found by other workers. McKay and Worthington suggested that this may be due to the fact that an unfavorable heat treatment was used. It consisted of annealing for 30 min. at 1000°C. (1830°F.), followed by furnace cooling. For example, Pilling and Ackerman found the corrosion of even 30 per cent chromium alloys in 5 per cent acid to be such that the alloys had to be considered to be in the active state. In the 35 per cent acid, however, alloys containing more than 10 per cent chromium, with or without nickel, were in the passive state, and losses ranged down to less than 1 mg. per sq. dm. per day.

Much has been published on the resistance of iron-nickel-chromium alloys to attack by acid solutions, but the larger proportion, as is indicated elsewhere, concerns alloys richer in chromium than in nickel. Among the reports are those of Utida and Saitô,[224] Hatfield,[189,303] Schmitz,[322] and Sauvageot and Lauprète.[361] However, inasmuch as such corrosion data are seldom comparable, it seems futile to do more than state that substantial quantities of these alloys are used in the making and handling of nitric acid. Practical experience seems to be the best guide. For example, a highly resistant alloy, according to laboratory test, will be attacked if halides are present in the acid.

218. Corrosion of Iron-nickel-chromium Alloys by Hydrochloric Acid.—Corrosion by hydrochloric acid of iron-nickel-

chromium alloys, judged by results of various investigations, is erratic. Alloys containing chromium are ordinarily highly susceptible to attack by this acid, but sometimes the passive state persists, with a resultant low rate of corrosion.

Pilling and Ackerman[316] used aerated and agitated 5 per cent hydrochloric acid in testing a large number of alloys. Under these conditions the passive state was not induced and weight losses ranged from 700 to 1000 mg. per sq. dm. per day for alloys containing more than 15 per cent nickel for all chromium contents up to 20 per cent. Guertler and Ackermann[274] determined by means of a microscope the time to produce visible attack on polished surfaces of alloys. No alloy withstood corrosion more than 2 hr. and the nickel-free alloys were most susceptible. Of the other available information, most is on alloys higher in chromium than nickel. The resistance of such alloys seems to be increased markedly by the addition of molybdenum. For detailed information, see "The Alloys of Iron and Chromium."

219. Corrosion of Iron-nickel-chromium Alloys by Sulphuric Acid.—Sulphuric acid, according to McKay and Worthington,[570] leads clearly to "a passivity-activity border-line condition." In the tests of Pilling and Ackerman,[316] in which aerated, agitated 5 per cent acid was used for alloys not in the best possible condition of heat treatment, passivity was not induced. The alloys contained up to 32 per cent chromium and variable nickel. McKay and Worthington quoted other results which show similar alloys (although confined to those higher in chromium than nickel) under other conditions to have been in the passive state, with losses less than 1 mg. per sq. dm. per day. Evidently, if the oxidizing power of the solution is great enough, the passive state is induced in spite of high hydrogen-ion concentration. According to Guertler and Ackermann,[274] iron-nickel-chromium alloys owe their resistance to sulphuric acid to the presence of nickel.

220. Corrosion of Iron-nickel-chromium Alloys by Sulphurous Acid.—According to the results of Pilling and Ackerman,[316] ferrous alloys containing high nickel, high chromium, or combinations of nickel and chromium successfully resist sulphurous acid solutions. McKay and Worthington[570] stated that properly made alloys containing at least 18 per cent chromium and 8 per cent nickel have substantially unlimited life in such

service as sulphite digestors in the paper industry. Attack is likely to be rapid, however, if the sulphurous acid is contaminated by sulphuric or hydrochloric acid. Many paper mills now prefer alloys containing 20 per cent chromium, 9 per cent nickel, and 3 per cent molybdenum, since they have greater resistance to contaminated sulphurous acid solutions.[546]

221. Corrosion of Iron-nickel-chromium Alloys by Phosphoric Acid.—Reported results for corrosion by phosphoric acid are at great variance. Pilling and Ackerman[316] found alloys containing 15 per cent chromium and up to 20 per cent nickel to be in the active state when tested in aerated, agitated 5 per cent acid at 30°C. (85°F.). Sanfourche and Portevin[397] and others have found the iron-nickel-chromium alloys to be passive under some conditions and active under others. What these conditions are is not clear, although impurities in the acid seem to have a definite effect.

222. Corrosion of Iron-nickel-chromium Alloys by Organic Acids.—Alloys containing at least 18 per cent chromium and 8 per cent nickel ordinarily resist organic acid solutions such as acetic, formic, citric, lactic, malic, oxalic, and tartaric at room temperature. At boiling temperatures, they may be attacked, especially if nickel content is low; for more details, see "The Alloys of Iron and Chromium" and McKay and Worthington.[570]

C. SCALING

The attack of metals by air at elevated temperatures seems to be governed by physical more than by chemical factors. Rate of oxidation, for example, depends upon the rate at which oxygen comes in contact with metal. The thickness attained by the film depends upon such factors as temperature, time, and the presence of gases other than oxygen. (More details can be found in Evans'[528] review of "Theoretical Aspects of Oxidation.")

Once a continuous film is formed, further oxidation must proceed by diffusion of oxygen through the oxide layer. In consideration of this fact, one worker arrived at the conclusion that the logarithm of the reaction constant should be a linear function of reciprocal absolute temperature; this was upheld by experiment.

The effect of time on the thickness of the oxide film caused by either oxygen or air can be accounted for by simple relationships.

For ferrous metals—and others that form non-porous films—the rate of thickening of the film is inversely proportional to the thickness of the film. In the integrated form it is

$$y^2 = kt + K$$

where y is the thickness of the film, k and K are constants, and t is time. The equation, of course, is that of a parabola. Thus, in the absence of other factors, the rate of oxidation declines with increasing time, consequently a continuously increasing resistance to further oxidation builds up. (The equation is not valid for low gas pressures or for very thin films.) Deviation from the parabolic equation is often true of alloys; this seems to be caused, at least in part, by interaction of the film and the metal. It is shown later, for example, that the outer layers of scale on iron-nickel alloys are nearly nickel free, but that the innermost layer may contain considerable nickel as free metal.

Practically speaking, the inference from the equation that in time there can be built up a virtually perfect protective coating breaks down because of cracking of the coating. According to Evans,[528] cracking and peeling of films in service are often to be ascribed to bending or cycles of heating and cooling. But even in the absence of such stresses, cracking may result: when the metal surface is converted to oxide, volume changes leave the film in a state of compression, and it can be shown that these stresses result in cracking when the thickness of the film exceeds a limiting value.

223. The Constitution of Scale.—In 1916, Stead[122] reported that the scale of nickel steels consists of several layers and that the nickel content of the layers differs widely. For example, the outermost layer of scale on a 25 per cent nickel steel consisted mainly of iron oxide, whereas the innermost layer included particles of metal containing 76 per cent nickel. These findings were amply verified by Pfeil,[315] who found the scale on iron and steel to consist of three layers. On a 2.75 per cent nickel steel, the outermost layer of scale contained no nickel, the middle layer 0.16 per cent, and the innermost layer 7.07 per cent. The microstructure of this scale differed from that on iron and carbon steels.

First, the inner layer contained minute metallic particles embedded in the oxide. Secondly, intercrystalline penetration into the metallic

core was more pronounced. Thirdly, beyond the range of inter-crystalline oxidation of the core an altered zone could be seen in the metal. In this zone an enormous number of extremely minute specks, probably of iron oxide could be seen.

Similar results were found with a 36 per cent nickel alloy. Nickel contents of the layers of scale, progressing inward, were 1.46, 2.29, and 52.08 per cent. Preferential distribution was found in scale on a steel containing 3.18 per cent nickel and 0.85 per cent chromium also, for the alloy content of the innermost layer was three times that of the core. Recent data obtained by Scheil and Kiwit[541] also showed preferential distribution of nickel in the scale. Analysis of oxide layers led them to the conclusion that iron diffuses, but not oxygen.

224. Influence of Nickel on the Scaling of Iron.—Nickel, at least in the range of concentration of alpha-phase alloys, does not increase the resistance of iron to scaling. (This is true also of other alloying elements; seemingly there are no low-alloy steels having marked resistance to scaling.) One early report, by Marble,[153] even showed a 5 per cent nickel alloy to have less resistance than a medium-carbon steel. More recent data by Scheil and Kiwit[541] show definitely that nickel does not increase resistance to scaling; they are given in Table 130. Results of Hatfield[255] indicated that a 3.25 per cent nickel steel was more resistant than iron to furnace gases at 900°C. (1650°F.), but not enough so to be interesting.

TABLE 130.—SCALING OF SOME LOW-NICKEL IRON-NICKEL ALLOYS*

Nickel, per cent	Weight loss, g. per sq. cm., after			
	15 hr. at 900°C. (1650°F.)	7.5 hr. at 1000°C. (1830°F.)	5 hr. at 1100°C. (2010°F.)	2 hr. at 1200°C. (2190°F.)
0.63	0.0685	0.1280	0.1155	0.1108
1.20	0.0648	0.1100	0.1065	0.1100
2.20	0.0713	0.1310	0.1095	0.1023

* Scheil and Kiwit.[541]

According to data of Marble[153] and of Dickenson,[174] the resistance of a 25 per cent nickel steel is somewhat better than that of low-nickel steels, but still not enough to make this a

material worthwhile for applications requiring high resistance to scaling.   This is likewise true of 35 per cent nickel steels; for example, Heindlhofer and Larsen[450] found the rate for this material to be about a third of that of iron.

225. Iron-nickel-chromium Alloys.—Alloys of iron, nickel, and chromium of the "high-alloy" kind are widely used for high-temperature service because of, among other things, their resistance to scaling.   According to Geiger,[529] there are four favored composition ranges:

    I. 50 to 65 per cent nickel, 12 to 20 per cent chromium.
    II. 30 to 40 per cent nickel, 15 to 20 per cent chromium.
    III. 10 to 20 per cent nickel, 25 to 30 per cent chromium.
    IV. 75 to 80 per cent nickel, 12 to 20 per cent chromium.

Alloys of range I are well known as "nichromes"; a typical composition is 60 per cent nickel and 15 per cent chromium. They are tough and have high resistance to attack by oxygen, nitrogen, and carbon.

Alloys of range II are widely used in furnace construction. Such alloys have low resistance to attack by sulphur gases. Where these are to be resisted, alloys containing more chromium than nickel are used (composition range III).   Alloys of range IV, which contain only about 6 per cent iron, have high resistance to oxidation up to about 1100°C. (about 2000°F.) and resistance to reducing gases containing sulphur up to about 540°C. (1000°F.).

Since alloys of the nichrome type were developed for electric-heating units, it is natural that much of the information on them has resulted from "life tests" of wires heated electrically. Hunter and Jones,[177] for example, used the change of resistance at an operating temperature of about 1000°C. (1830°F.) as a measure of the progress of oxidation.   It is likely, however, that data obtained by other methods are of greater interest.

There is relatively little information on systematic study of variation with composition of the resistance to oxidation of iron-nickel-chromium alloys.   Dean[335] prepared 24 alloys from electrolytic materials in a high-frequency furnace.   The specimens were heated at 1000°C. (1830°F.) for periods of 20 hr. At the end of each heating, oxidation was determined by removal of the scale.   Two distinct types of scale were found; one, characteristic of iron-nickel alloys and of iron-rich ternary alloys,

was pervious to oxygen; the other, characteristic of nickel-chromium alloys, was impervious, hence suitable for high-temperature service. The dividing line established by Dean is shown in Fig. 287; it extends from the nickel vertex to the point representing 23 per cent chromium and 77 per cent iron. All alloys richer in chromium, therefore, should have possibilities as materials resistant to oxidation. The other dotted line marks

FIG. 287.—Fields of scale-resisting iron-nickel-chromium alloys. (Dean.[335])

the limit of cold rolling without difficulty. Alloys richer in chromium were either difficult or impossible to roll, even with frequent intermediate annealing. Points shown in three different regions of Fig. 287 indicate compositions of commercial alloys. Somewhat similar to Dean's diagram is that of Scheil and Kiwit,[541] shown in Fig. 288, although the boundary lines here were determined only by arbitrarily chosen weight losses. Alloys of field A, which lost less than 0.001 g. per sq. cm. in 7.5 hr. at 1000°C. (1830°F.), were considered satisfactory. Their scale was characterized by the presence of chromium oxide (Cr_2O_3)

only.   It was deduced also that the stability of the scale increased
with increased chromium content.   This is indicated also by

FIG. 288.—Oxidation losses of iron-nickel-chromium alloys (field A, less than
0.001 g. per cu. cm.; field B, less than 0.01 g. per cu. cm.; field C, more than 0.01
g. per cu. cm.) (*Scheil and Kiwit.*[541])

Dean's data, in the form presented by Pilling and Worthing-
ton,[395] shown in Fig. 289.   Curves show the average weight loss

FIG. 289.—The oxidation of iron-nickel-chromium alloys.   (*Dean, as reported by
Pilling and Worthington.*[395])

per heating cycle of alloys of constant iron-nickel ratio as a
function of chromium content.

TABLE 131.—OXIDATION OF SOME COMMERCIAL RESISTANCE WIRES AT
1100°C. (2010°F.)*

Mark	Composition, per cent							Oxidation after 5 hr. at 1100°C. (2010°F.), mg. oxygen per sq. cm. of surface
	Ni	Cr	Fe	C	Mn	Si	Al†	
A	59.8	15.6	23.2	0.37	1.5	0.1	1.7	1.28
B	67.7	20.9	8.9	0.47	1.7	0.2	1.4	0.84
C	80.2	17.8	1.2	0.21	0.5	0.3	3.1	0.68
D	75.5	18.5	4.0	0.07	1.0	0.3	1.0	0.98
E	62.0	10.5	25.6	0.07	1.4	0.2	1.2	6.00
F	63.0	11.8	23.1	0.46	1.4	0.2	1.6	1.38
G	83.1	13.2	3.0	0.35	0.1	0.4	1.3	1.19

* Utida and Saitô.[205]

† According to Pilling and Worthington,[395] the makers of these alloys stated that aluminum is not a component.

Oxidation tests of relatively short duration on commercial resistance wires were made by Utida and Saitô.[205] Composition and oxidation after 5 hr. at 1100°C. (2010°F.) are given in Table 131. The progress of oxidation was followed continuously,

FIG. 290.—The influence of time on the oxidation of some high-nickel alloys. (*Utida and Saitô*[205] *as reported by Pilling and Worthington.*[395])

and these data permitted construction of Fig. 290, which is given as revised by Pilling and Worthington. These curves show vividly the resistance to oxidation of chromium-bearing

alloys as compared with nickel. Alloy *E* formed a brittle scale which afforded little protection. The only marked difference of composition between this alloy and alloy *F* seems to be in carbon content. Whether or not this difference is significant is not known, and no improvement can be made on Pilling and Worthington's statement that "some of the complicating factors may be very subtle. . . . " Another example of this was reported by Rohn.[265] Five alloys (14 to 15 per cent chromium, 63 to 65 per cent nickel) from different sources showed markedly different resistance to oxidation.

Several investigators, notably Kayser,[418] have studied scaling by cumulative tests at successively higher temperatures. Kayser, for example, heated specimens at 700°C. (1290°F.) for 18 hr. Those showing no scale were replaced at a temperature of 750°C. (1380°F.). This procedure was repeated at 50°C. (90°F.) intervals until scale appeared. Results on alloys of interest here are collected in Table 132.

TABLE 132.—SCALING TEMPERATURES OF VARIOUS ALLOYS*

Composition, per cent			Scaling range	
C	Ni	Cr	°C.	°F.
0.9	66	21	1200 to 1250	2190 to 2280
0.8	60	20	1200 to 1250	2190 to 2280
1.4	30	30	1050 to 1100	1920 to 2010
0.8	..	28	1050 to 1100	1920 to 2010
0.7	57	15	1150 to 1200	2100 to 2190
0.5	21	14	1050 to 1100	1920 to 2010
0.3	..	28	1050 to 1100	1920 to 2010
0.2	8	18	900 to 950	1650 to 1740

* Kayser.[418]

The resistance to scaling of iron-nickel-chromium alloys is markedly affected by atmospheres containing sulphur gases. Much of the available information was supplied by Kayser[190,385] and by Hatfield.[255] In the first report, Kayser found alloys of the nichrome type to have high resistance to steam, carbon dioxide, ammonia, and oxygen, either singly or in mixtures. The introduction of hydrogen sulphide or sulphur dioxide, however, destroyed the resistance of even the best alloys. He

ascribed the effect to the easy formation of a low-melting nickel sulphide. According to Pilling and Worthington, the temperature and the degree of oxidation are of great importance. For example, at high temperature, and with sulphur completely oxidized, "even pure nickel may be exposed to strong concentrations of sulphur with apparently no action other than a normal amount of oxidation." On the other hand, at low temperature, or with enough hydrogen present, "attack may be both rapid and of a particularly damaging and penetrating nature." The effect of increased iron and chromium contents is not clear, although it is known qualitatively that both elements increase resistance to attack by sulphur. This is in general agreement with a statement of Kayser's.[385]

Reducing atmospheres containing sulphur dioxide or hydrogen sulphide are the most dangerous atmospheres with which heat-resisting alloys have to contend. It has not been established what is the permissible percentage of sulphur dioxide or hydrogen sulphide that the different alloys can withstand, but it is known that when the sulphur content of the original fuel exceeds some 1.5 to 2 per cent the life of 25 per cent nickel alloys is seriously shortened whereas nickel-free heat-resisting alloys are immune from attack.

Thus, only trends are known. But this is true of all corrosive agents that attack by penetration.

Still other substances promote attack by fluxing the protective oxide coating; among them, Pilling and Worthington cited lead oxide, sodium compounds, borax, and copper oxide. Some alloys are attacked by molten alloys of low melting point, such as aluminum, antimony, bismuth, and tin.

Under certain conditions chromium may be attacked by nitrogen, as in apparatus for nitrogen fixation. Certain high-nickel iron-nickel-chromium alloys are resistant, according to Vanick.[206] Materials for this service were discussed also by Thompson,[247] Raffo,[318] and Bosch.[442] Still another type of service for which iron-nickel-chromium alloys are used is in nitriding and carburizing, for which the retort or pot must resist absorption of nitrogen or carbon. Carburizing pots usually contain 30 to 70 per cent nickel and 15 to 20 per cent chromium.

226. Other Complex Iron-nickel Alloys.—Iron-nickel-aluminum alloys in certain composition ranges have been known for

some years to have high resistance to scaling. Brophy,[172] for example, reported such an alloy in 1922. Later, Gruber[340] found that the addition of aluminum rendered some iron-nickel-chromium alloys resistant to attack by sulphur-bearing gases. An alloy containing 60 per cent nickel, 15 per cent chromium, 4 per cent manganese, and 5 per cent aluminum was resistant up to 800°C. (1470°F.). Increase of aluminum content to 10 per cent caused the material to be resistant at all temperatures. Further increase of aluminum content resulted in no further improvement. Gruber ascribed the effect of aluminum to increasing the melting temperature of the sulphide formed and to the formation of a dense scale containing alumina.

Hatfield's[255] comprehensive investigation of scaling included iron-nickel-chromium alloys containing tungsten or silicon. He concluded that both elements increase resistance. Other data, by Losana,[353] on alloys more properly considered in "The Alloys of Iron and Chromium" do not support this conclusion for tungsten, however. An earlier statement by Mahoux[217] on automotive engine valves seems to support Losana. A chromium-tungsten steel containing 22 per cent nickel was attacked severely, whereas a chromium-tungsten steel without nickel was not. Opposed to this is the fact that Johnson and Christiansen[200] found iron-chromium-tungsten alloys unsatisfactory because of scaling. They found iron-nickel-chromium-silicon alloys (20 to 25 per cent nickel, 6 to 15 per cent chromium) to be unsatisfactory also. Musatti and Reggiori,[503] however, concluded that austenitic iron-nickel-chromium alloys containing tungsten and silicon are the best material for valves.

On the whole, therefore, knowledge of the resistance to scaling of complex alloys is very incomplete and often conflicting. Pilling and Worthington's[395] statement in 1931 remains true: The facts of heat-resisting metals "rest upon a rather indefinite sensing of behavior under practical conditions in which successful use is the guiding principle."

D. AUTHOR'S SUMMARY

1. Alloys of iron and nickel generally have higher resistance to corrosion than ordinary irons and steels, but not enough so to cause them to be used for this reason alone. Certain of the

special-purpose alloys, such as those having low thermal expansion, are highly resistant to attack by the atmosphere and by water, especially when polished.

2. The iron-nickel-chromium alloys are the most versatile of the ferrous metals used primarily for their resistance to corrosion. On the basis of amount in use, those containing more chromium than nickel are of greater importance. Of the two important reasons for adding nickel, one is to produce gamma-phase alloys because of their more satisfactory mechanical properties, the other is to take advantage of special corrosion behavior contributed by nickel. Higher nickel than chromium content is supposed to be advantageous in such instances as neutral chloride solutions and acid solutions of low oxidizing power.

3. Iron-nickel-chromium alloys are much used for equipment for the making and handling of nitric acid. The nickel content of alloys for this purpose is relatively unimportant. For the handling of sulphuric acid, however, the presence of nickel seems to be necessary.

4. Iron-nickel-chromium alloys, if properly made, ordinarily have satisfactory resistance to attack by organic acids.

5. The scale on iron-nickel alloys is like that on certain other alloys in that it contains free metal as well as oxides. It is common for the innermost layer of scale on iron-nickel alloys to contain more nickel than the core.

6. Nickel in small amounts does not increase the resistance of iron to scaling. The addition of 25 to 35 per cent nickel causes perceptible increase of resistance to scaling, but not enough to cause such alloys to be used for this reason. Still higher nickel content plus up to about 20 per cent chromium yields the most satisfactory resistance to oxidation. Such alloys, however, are attacked rapidly by gases that contain compounds of sulphur. For these atmospheres, the most satisfactory alloys contain 25 to 30 per cent chromium and 10 to 20 per cent nickel. The nichrome alloys, of which a composition of 60 per cent nickel and 15 per cent chromium is typical, have high resistance to attack by oxygen, nitrogen, and carbon. Furthermore, they are mechanically tough.

7. Aluminum is an important addition element to heat-resisting metals. Iron-nickel-aluminum alloys have high resistance to oxidation, and it has been reported that the addition

of 10 per cent aluminum to an alloy of the nichrome type caused it to be resistant to gases containing sulphur compounds.

8. On the whole, information on corrosion of iron-nickel and more complex alloys is incomplete and often conflicting. Practical knowledge continues to be a very important factor in the application of special alloys to the needs of industry.

BIBLIOGRAPHY

Before 1900

1. CRONSTEDT,· A. F.: Om en ny Metall-art (A New Metal), *Kongl. Svenska Vetenskaps Akad. Handlingar*, v. 12, 1751, pp. 287–292.
2. STODART, J., and M. FARADAY: Experiments on the Alloys of Steel, Made with a View to Its Improvement, *Quarterly J. Sci. Lit. Arts*, v. 9, No. 18, 1820, pp. 319–330 (324). Also: *Phil. Trans. Royal Soc.*, London, 1822, pp. 253–270.
3. BERTHIER, P.: Analyse du fer météorique de Toluca au Mexique (Analysis of the Meteoric Iron of Toluca, Mexico), *Ann. des Mines*, ser. 2, v. 1, 1827, pp. 337–338.
4. LIEBIG, J. VON: Stahl (Steel), *Ann. d. Pharmacie*, v. 2, 1832, p. 237.
5. JOULE, J. P.: On the Effects of Magnetism upon the Dimensions of Iron and Steel Bars, *Phil. Mag.*, ser. 3, v. 30, 1847, pp. 76–87, 225–241.
6. FAIRBAIRN, W.: Experiments to Determine the Properties of Some Mixtures of Cast Iron and Nickel, *Mem. Lit. Phil. Soc.*, Manchester, ser. 2, v. 15, 1858, pp. 104–112.
7. BARRETT, W. F.: On the Alterations in the Dimensions of the Magnetic Metals by the Act of Magnetisation, *Nature*, v. 26, 1882, pp. 585–586.
8. RAYLEIGH (Lord): Notes on Electricity and Magnetism.—III. On the Behavior of Iron and Steel under the Operation of Feeble Magnetic Forces, *Phil. Mag.*, ser. 5, v. 23, 1887, pp. 225–245.
9. HOPKINSON, J.: Magnetic Properties of Alloys of Nickel and Iron, *Proc. Royal Soc.*, London, v. 47, 1889–1890, pp. 23–24.
10. HOPKINSON, J.: Physical Properties of Nickel Steel, *Proc. Royal Soc.*, London, v. 47, 1889–1890, pp. 138–139.
11. RILEY, J.: Alloys of Nickel and Steel, *J. Iron Steel Inst.*, 1889, I, pp. 45–77.
12. HOPKINSON, J.: Magnetic Properties of Alloys of Nickel and Iron, *Proc. Royal Soc.*, London, v. 48, 1890, pp. 1–13.
13. LECHATELIER, H.: Sur la résistance électrique du fer et de ses alliages aux températures élevées (Electric Resistance of Iron and Its Alloys at Elevated Temperatures), *C. R. Acad. Sci.*, Paris, v. 110, 1890, pp. 283–286.
14. LECHATELIER, A.: Influence de la température sur les propriétés mécaniques des métaux (Influence of Temperature on Mechanical Properties of Metals), *Génie Civil*, v. 19, 1891, pp. 59–60, 73–74, 107–110.
15. MERCADIER, E.: Sur la détermination des constants et du coefficient d'élasticité de l'acier-nickel (The Determination of Constants and of the Coefficient of Elasticity of Nickel Steel), *C. R. Acad. Sci.*,

Paris, v. 113, 1891, pp. 33–36.   Abst.: *Eng. Min. J.*, v. 52, 1891, p. 270.

16. HOWARD, J. E.: Nickel Steel from Ordnance Bureau U. S. Navy, Nos. 4816, 4817, in "Tests of Metals," U. S. Arsenal, Watertown, Mass., 1893, pp. 237–238.

17. LeCHATELIER, A.: Discussion of paper by R. A. Hadfield on The Results of Heat Treatment on Manganese Steel and Their Bearing upon Carbon Steel, *J. Iron Steel Inst.*, v. 45, 1894, pp. 207–210.

18. MOULAN, P.: Le ferro-nickel (Iron-nickel Alloys), *Rev. Univ. Mines*, v. 27, 1894, pp. 142–152.   Abst.: *J. Iron Steel Inst.*, v. 46, 1894, pp. 457–458.

19. BESSEMER, H.: Correspondence on paper by H. A. Wiggin on Nickel Steel, and Its Advantages over Ordinary Steel, *J. Iron Steel Inst.*, v. 48, 1895, pp. 164–209 (191–195).

20. GARRISON, F. L.: Carbides of Iron, *J. Franklin Inst.*, v. 140, 1895, pp. 464–472.

21. HOWARD, J. E.: Nickel Steel from Springfield Armory, Nos. 5309, 5401, 5520, 5521, in "Tests of Metals," U. S. Arsenal, Watertown, Mass., 1896, pp. 60–67, 431

22. RUDELOFF, M.: Die Eigenschaften von Nickel-Eisen-Legierungen (The Properties of Nickel-iron Alloys), *Verh. d. Ver. z. Beförderung d. Gewerbefleisses*, 1896, pp. 65–84.   Abst.: *Oesterreichische Z. f. Berg- u. Hüttenwesen*, v. 44, 1896, pp. 240–241.

23. GUILLAUME, CH.-ED.: Sur la dilatation des aciers au nickel (Dilatation of Nickel Steels), *C. R. Acad. Sci.*, Paris, v. 124, 1897, pp. 176–179.

24. GUILLAUME, CH.-ED.: Recherches sur les aciers au nickel.   Propriétés métrologiques (Investigation of Nickel Steels.   Metrological Properties), *C. R. Acad. Sci.*, Paris, v. 124, 1897, pp. 752–755.

25. GUILLAUME, CH.-ED.: Recherches sur les aciers au nickel.   Dilatation aux températures élevées; résistance électrique (Investigation of Nickel Steels.   Dilatation at High Temperatures; Electric Resistivity), *C. R. Acad. Sci.*, Paris, v. 125, 1897, pp. 235–238, 342.

26. GUILLAUME, CH.-ED.: Recherches sur le nickel et ses alliages (Investigations on Nickel and Its Alloys), *Arch. Sci. Phys. et. Nat.*, ser. 4, v. 5, 1898, pp. 255–280, 305–330.

27. GUILLAUME, CH.-ED.: L'équilibre chimique dans les solides et les aciers au nickel (Chemical Equilibrium in Solids and in Nickel Steels), *Rev. Générale Sci.*, v. 9, 1898, pp. 282–286.

28. HOWARD, J. E.: Nickel Steel Rifle Barrels, in "Tests of Metals," U. S. Arsenal, Watertown, Mass., 1898, pp. 391, 690.

29. RUDELOFF, M.: Fünfter Bericht des Sonderausschusses für Eisenlegierungen (Fifth Report of the Iron Alloys Committee), *Verh. d. Ver. z. Beförderung d. Gewerbefleisses*, v. 77, 1898, pp. 327–348.   Abst.: *Stahl u. Eisen*, v. 22, 1902, pp. 1287–1292.

30. BROWNE, D. H.: Nickel Steel—A Synopsis of Experiment and Observation, *Trans. Am. Inst. Min. Eng.*, v. 29, 1899, pp. 569–648.

31. HADFIELD, R. A.: Alloys of Iron and Nickel, *Min. of Proc. Inst. Civil Eng.*, v. 138, 1899, pp. 1–167.

32. HOWARD, J. E.: Nickel Steel, in "Tests of Metals," U. S. Arsenal, Watertown, Mass., 1899, p. 679.

33. MACLEAN, M.: On the Effect of Strain on the Thermoelectric Qualities of Metals—Part II, *Proc. Royal Soc.*, London, v. 66, 1899–1900, pp. 165–178.

34. OSMOND, F.: Sur les alliages de fer et de nickel (The Alloys of Iron and Nickel), *C. R. Acad. Sci.*, Paris, v. 128, 1899, pp. 304–307.

35. TILDEN, W. A.: On the Specific Heat of Metals and the Relation of Specific Heat to Atomic Weight, *Proc. Royal Soc.*, London, v. 66, 1899–1900, pp. 244–247.

1900–1909

36. STEINMANN, É.: Recherches sur la thermo-électricité de quelques alliages (The Thermoelectricity of Some Alloys), *Arch. Sci. Phys. et Nat.*, ser. 4, v. 9, 1900, pp. 413–452; v. 10, 1900, p. 25.

37. HOWE, H. M.: Effets relatifs de la corrosion sur le fer, l'acier doux et l'acier au nickel dans l'air, l'eau de mer et l'eau ordinaire (Relative Corrosion of Iron, Mild Steel, and Nickel Steel upon Exposure to Air, Salt Water, and Tap Water), *Congr. Intern. Méth. d'Essai Mat. Constr.*, Paris, 1900, v. 2, part 1, 1901, pp. 229–266.

38. BARRETT, W. F.: On the Increase of Electrical Resistivity Caused by Alloying Iron with Various Elements, and the Specific Heat of Those Elements, *Proc. Royal Soc.*, London, v. 69, ser. A, 1902, pp. 480–485.

39. BARRETT, W. F., W. BROWN, and R. A. HADFIELD: Researches on the Electrical Conductivity and Magnetic Properties of Upwards of One Hundred Alloys of Iron, *J. Inst. Elec. Eng.*, v. 31, 1902, pp. 674–729.

40. BELLOC, G.: Sur la thermo-électricité des aciers et des ferronickels (Thermoelectricity of Steel and Iron-nickel Alloys), *C. R. Acad. Sci.*, Paris, v. 134, 1902, pp. 105–106.

41. DUMAS, L.: Recherches sur les aciers au nickel à hautes teneurs (Investigation of High-nickel Steels), *Ann. des Mines*, ser. 10, v. 1, 1902, pp. 357–561.

42. HONDA, K., and S. SHIMIZU: Change of Length of Ferromagnetic Wires under Constant Tension in Magnetisation, *Phil. Mag.*, ser. 6, v. 4, 1902, pp. 339–346.

43. NAGAOKA, H., and K. HONDA: On the Magnetostriction of Steel, Nickel, Cobalt, and Nickel Steels, *Phil. Mag.*, ser. 6, v. 4, 1902, pp. 45–72.

44. ANGENHEISTER, G.: Beiträge zur Kenntnis von der Elastizität der Metalle (Contributions to the Knowledge of the Elasticity of Metals), *Ann. d. Physik*, ser. 4, v. 11, 1903, pp. 188–201.

45. BUTLER, J. G.: Tests of 30 Per Cent Nickel Steel Billet, in "Tests of Metals," U. S. Arsenal, Watertown, Mass., 1903, pp. 401–408.

46. CHARPY, G., and L. GRENET: Recherches sur la dilatation des aciers aux températures élevées (Investigation of the Dilatation of Steels at High Temperature), *Bull. Soc. d'Encouragement Ind. Nat.*, v. 102, 1903, pp. 464–507.

47. COLBY, A. L.: "A Comparison of Certain Physical Properties of Nickel Steel and Carbon Steel Proving the Superiority of Nickel Steel over Carbon Steel for Bridge and Structural Purposes," The International Nickel Company, Inc., New York, 1903, 103 pages.

48. COLBY, A. L.: Non-corrosive Nickel Steel Boiler Tubes, *Trans. Soc. Naval Arch. and Marine Eng.*, v. 11, 1903, pp. 115–137.

49. DIEGEL: Das Verhalten einiger Metalle in Seewasser (The Behavior of Some Metals in Salt Water), *Verh. d. Ver. z. Beförderung d. Gewerbefleisses*, v. 5, 1903, Nos. 3–5. Extract: *Stahl u. Eisen*, v. 24, 1904, pp. 567–574, 629–642.

50. DUMAS, L.: Propriétés mécaniques des aciers au nickel magnétiques et non magnétiques (Mechanical Properties of Magnetic and Non-magnetic Nickel Steels), *Bull. Soc. de l'Ind. Minérale*, ser. 4, v. 2, 1903, pp. 641–688.

51. GUILLAUME, CH.-ED.: Changements passagers et permanents des aciers au nickel (Transitory and Permanent Changes of Nickel Steels), *C. R. Acad. Sci.*, Paris, v. 136, 1903, pp. 356–358.

52. HADFIELD, R. A.: Alloys of Iron, Manganese, and Nickel, *Supplement to Min. of Proc. Inst. Civil Eng.*, v. 154, 1903, pp. 118–122.

53. NAGAOKA, H., and K. HONDA: Magnetization and Magnetostriction of Nickel Steels Containing Different Percentages of Nickel, *J. Coll. Sci.*, Tokyo Imp. Univ., v. 19, 1903, No. 11, 13 pp.

54. TILDEN, W. A.: The Specific Heats of Metals and the Relation of Specific Heat to Atomic Weight, Part II, *Proc. Royal Soc.*, London, v. 71, 1903, p. 220.

55. WILLIAMS, W. E.: The Influence of Stress and of Temperature on the Magnetic Change of Resistance in Iron, Nickel, and Nickel Steel, *Phil. Mag.*, ser. 6, v. 6, 1903, pp. 693–697.

56. GUILLET, L.: "Les Aciers Spéciaux" (Special Steels), Dunod, Paris, v. 1, 1904, pp. 1–46.

57. GUYE, CH.-E., and A. SCHIDLOF: L'hystérèse magnétique aux fréquences élevées dans le fer, le nickel et les aciers au nickel (Magnetic Hysteresis at High Frequencies in Iron, Nickel, and Nickel Steels), *Arch. Sci. Phys. et Nat.*, ser. 4, v. 18, 1904, pp. 576–593; v. 19, 1905, pp. 60–79, 159–187.

58. OSMOND, F., and G. CARTAUD: Sur les fers météoriques (Meteoric Iron), *Rev. de Mét.*, *Mém.*, v. 1, 1904, pp. 69–79.

59. CARPENTER, H. C. H., R. A. HADFIELD, and P. LONGMUIR: Seventh Report to the Alloys Research Committee: On the Properties of a Series of Iron-nickel-manganese-carbon Alloys, *Proc. Inst. Mech. Eng.*, 1905, parts 3–4, pp. 857–1041.

60. GUERTLER, W., and G. TAMMANN: Über die Legierungen des Nickels und Kobalts mit Eisen (Iron-nickel and Iron-cobalt Alloys), *Z. anorg. Chemie*, v. 45, 1905, pp. 205–224.

61. GUILLET, L.: Aciers nickel-manganèse (Nickel-manganese Steels), *Rev. de Mét.*, *Mém.*, v. 2, 1905, pp. 825–841.

62. HADFIELD, R. A.: Experiments Relating to the Effect on Mechanical and Other Properties of Iron and Its Alloys Produced by Liquid-air

Temperature, *J. Iron Steel Inst.*, v. 67, 1905, pp. 147–255. Preliminary, by J. Dewar and R. A. Hadfield, in *Proc. Royal Soc.*, London, v. 74, 1905, pp. 326–336.

63. HONDA, K., and S. SHIMIZU: On the Magnetisation and the Magnetic Change of Length in Ferromagnetic Metals and Alloys at Temperatures Ranging from −186°C. to +1200°C., *Phil. Mag.*, ser. 6, v. 10, 1905, pp. 548–574, 642–661.

64. WATERHOUSE, G. B.: The Influence of Nickel and Carbon on Iron, *J. Iron Steel Inst.*, v. 68, 1905, pp. 376–407. Also: *Electrochem. Met. Ind.*, v. 4, 1906, pp. 451–453, 482–486.

65. WILLIAMS, W. E.: On the Magnetic Change of Resistance in Iron, Nickel, and Nickel Steel at Various Temperatures, *Phil. Mag.*, ser. 6, v. 9, 1905, pp. 77–85.

66. BENEDICKS, C.: Fysikaliska och fysikaliskt-kemiska undersökningar öfver kolstål (Physical and Physico-chemical Investigations on Carbon Steel), *Jernk. Ann.*, v. 90 (61), 1906, pp. 1–231.

67. GUILLET, L.: Quaternary Steels, *J. Iron Steel Inst.*, v. 70, 1906, pp. 1–141.

68. BROWN, W.: The Densities and Specific Heats of Some Alloys of Iron, *Sci. Trans. Royal Dublin Soc.*, ser. 2, v. 9, 1905–1909 (1907), pp. 59–84.

69. SMITH, S. W. J.: The Thermomagnetic Analysis of Meteoric and Artificial Nickel-iron Alloys, *Proc. Royal Soc.*, London, v. 79, ser. A, 1907, pp. 132–133.

70. GUYE, CH.-E., and H. WOELFLE: Étude sur les variations du IIe module d'élasticité de l'invar en fonction de la température (The Variations of the Shear Modulus of Invar as Depending on Temperature), *Arch. Sci. Phys. et Nat.*, ser. 4, v. 24, 1908, pp. 62–76, 159–171.

71. BURGESS, C., and J. ASTON: Physical Properties of Iron-copper Alloys, *Trans. Am. Electrochem. Soc.*, v. 16, 1909, pp. 241–256. Also: *Electrochem. Met. Ind.*, v. 7, 1909, pp. 436–438. Also: *Iron Age*, v. 84, 1909, pp. 1476–1479.

72. DUMAS, A.: Chaleur spécifique des substances ferromagnétiques. Alliages de fer et de nickel (Specific Heat of Ferromagnetic Substances. Alloys of Iron and Nickel), *Arch. Sci. Phys. et Nat.*, ser. 4, v. 27, 1909, pp. 352–382, 453–478.

73. GIESEN, W.: The Special Steels in Theory and Practice, *Iron Steel Inst., Carnegie Schol. Mem.*, v. 1, 1909, pp. 1–59.

74. GUILLET, L., and L. RÉVILLON: Expériences sur l'essai au choc à température variable (Impact Tests at Variable Temperature), *Rev. de Mét., Mém.*, v. 6, 1909, pp. 94–101.

75. GUILLET, L., and L. RÉVILLON: Nouvaux essais de choc à chaud sur les aciers ordinaires et les aciers spéciaux (New Impact Tests at High Temperatures on Ordinary and Special Steels), *Rev. de Mét., Mém.*, v. 6, 1909, pp. 918–924.

76. PORTEVIN, A.: Contribution à l'étude des aciers spéciaux ternaires (Contribution to the Study of Ternary Alloy Steels), *Rev. de Mét.*,

Mém., v. 6, 1909, pp. 1264–1362.   Also: *Iron Steel Inst., Carnegie Schol. Mem.*, v. 1, 1909, pp. 230–364.

77. RÉVILLON, L.: Contribution à l'étude des aciers pour engrenages (Contribution to the Study of Gear Steels), *Rev. de Mét., Mém.*, v. 6, 1909, pp. 1024–1053.   Also: *Iron Steel Inst., Carnegie Schol. Mem.*, v. 1, 1909, pp. 161–218.

78. ROBIN, F.: Note additionnelle au mémoire sur la dureté à chaud des aciers (Addendum to the Article on Hardness of Steels at High Temperatures), *Rev. de Mét., Mém.*, v. 6, 1909, pp. 180–184.

79. RUER, R.: Das System Nickel-Eisen (The Iron-nickel System), *Metallurgie*, v. 6, 1909, pp. 679–680.

1910–1914

80. BURGESS, C. F., and J. ASTON: The Strength of the Alloys of Nickel and Copper with Electrolytic Iron, *University Wisconsin Bull.* 346, *Eng. Ser.*, v. 6, 1910, pp. 37–80.

81. BURGESS, C. F., and J. ASTON: The Magnetic and Electrical Properties of the Iron-nickel Alloys, *Met. Chem. Eng.*, v. 8, 1910, pp. 23–26.

82. FRIEDRICH, K., and A. LEROUX: Zur Kenntnis des Schmelzdiagramms der Nickel-Kohlenstofflegierungen (The Nickel-carbon Diagram), *Metallurgie*, v. 7, 1910, pp. 10–13.

83. GUILLET, L., and L. RÉVILLON: Nouvaux essais au choc à températures variables (New Impact Tests at Variable Temperatures), *Rev. de Mét., Mém.*, v. 7, 1910, pp. 837–844.

84. HEGG, F.: Étude thermomagnétique sur les ferro-nickels (Thermo-magnetic Study of Iron-nickel Alloys), *Arch. Sci. Phys. et Nat.*, ser. 4, v. 29, 1910, pp. 592–617; v. 30, 1910, pp. 15–45.

85. PANEBIANCO, G.: Sulla suscettibilità magnetica dei metalli ferro-magnetici in campi deboli (Magnetic Susceptibility of Ferromagnetic Materials in Weak Fields), *Rend. Accad. Sci. Fisiche e Mat.*, Napoli, ser. 3a, v. 16, 1910, pp. 216–221.

86. ROUSH, G. A.: Hardness Tests on Alloys of Nickel and Copper with Electrolytic Iron, I, *Chem. Met. Eng.*, v. 8, 1910, pp. 468–470.

87. RUER, R., and E. SCHÜZ: Das System Eisen-Nickel (The Iron-nickel System), *Metallurgie*, v. 7, 1910, pp. 415–426.

88. SCHIMPFF, H.: Über die Wärmekapazität von Metallen und Metall-verbindungen (The Specific Heat of Metals and Metal Compounds), *Z. physik. Chemie*, v. 71, 1910, pp. 257–300.

89. VOGEL, R.: Über das ternäre System Eisen-Kupfer-Nickel (The Ternary System Iron-copper-nickel), *Z. anorg. Chemie*, v. 67, 1910, pp. 1–16.

90. BAAR, M. VON: Über die Legierungen des Molybdäns mit Nickel, Mangans mit Thallium und des Calciums mit Magnesium, Thallium, Blei, Kupfer und Silber (The Alloys of Molybdenum and Nickel, of Manganese and Thallium, and of Calcium and Magnesium, Thallium, Lead, Copper, and Silver), *Z. anorg. Chemie*, v. 70, 1911, pp. 352–394.

91. BENEDICKS, C.: Synthèse du fer météorique (Synthesis of Meteoric Iron), *Rev. de Mét., Mém.,* v. 8, 1911, pp. 85–107.

92. BOUDOUARD, O.: Résistivité électrique des aciers spéciaux (Electric Resistivity of Special Steels), *C. R. Acad. Sci.,* Paris, v. 153, 1911, pp. 1475–1478. Also: *Rev. de Mét., Mém.,* v. 9, 1912, pp. 294–303.

93. COLVER-GLAUERT, E., and S. HILPERT: The Magnetic Properties of Some Nickel Steels with Some Notes on the Structure of Meteoric Iron, *J. Iron Steel Inst.,* v. 83, 1911, pp. 375–411 (see also reference 94).

94. HILPERT, S., and E. COLVER-GLAUERT: Über die magnetischen Eigenschaften von Nickelstahlen (Magnetic Properties of Nickel Steels), *Z. f. Elektrochemie,* v. 17, 1911, pp. 750–761 (see also reference 93).

95. KAYE, G. W. C.: A Silica Standard of Length, *Proc. Royal Soc.,* London, v. 85, ser. A, 1911, pp. 430–447.

96. McWILLIAM, A., and E. J. BARNES: Some Properties of Three Per Cent Nickel Steels, *J. Iron Steel Inst.,* v. 83, 1911, pp. 269–293.

97. BREGOWSKY, I. M., and L. W. SPRING: The Effect of High Temperatures on the Physical Properties of Some Alloys, *Proc. International Assoc. Test. Mat.,* VIth Congress, New York, 1912, VII-1, 16 pp.

98. BURGESS, C. F., and J. ASTON: Influence of Various Elements on the Corrodibility of Iron, *Trans. Am. Electrochem. Soc.,* v. 22, 1912, pp. 241–258.

99. COLVER-GLAUERT, E., and S. HILPERT: The Magnetic Properties of Nickel and Manganese Steels with Reference to Their Metallographic Constitution, *Trans. Faraday Soc.,* v. 8, 1912, pp. 134–148.

100. DUPUY, E. L., and A. PORTEVIN: Sur les propriétés thermo-électriques du système fer-nickel-carbone (Thermoelectric Properties of Iron-nickel-carbon Alloys), *C. R. Acad. Sci.,* Paris, v. 155, 1912, pp. 1082–1085.

101. HILPERT, S., E. COLVER-GLAUERT, and W. MATHESIUS: Über die magnetischen Eigenschaften von Nickel- und Manganstahlen (Magnetic Properties of Nickel and Manganese Steels), *Stahl u. Eisen,* v. 32, 1912, pp. 96–104.

102. HILPERT, S., and W. MATHESIUS: Über die magnetischen Eigenschaften von Mangan- und Nickelstahlen (Magnetic Properties of Manganese and Nickel Steels), *Z. f. Elektrochemie,* v. 18, 1912, pp. 54–64. Also: *J. Iron Steel Inst.,* v. 86, 1912, pp. 302–310.

103. PARRAVANO, N.: Le leghe ternarie di ferro-nichel-manganese, nichel-manganese-rame, ferro-manganese-rame (The Ternary Alloys of Iron-nickel-manganese, Nickel-manganese-copper, Iron-manganese-copper), *Gazz. Chim. Ital.,* v. 42, part 2, 1912, pp. 367–379, 385–394, 513–531. Also: *Internationale Z. f. Metallographie,* v. 4, 1913, pp. 171–202.

104. RUFF, O., and W. MARTIN: Über die Löslichkeit von Kohlenstoff in Nickel (The Solubility of Carbon in Nickel), *Metallurgie,* v. 9, 1912, pp. 143–148.

105. DANNECKER, C.: Über doppelte neutrale Punkte und die elektromotorischen Kräfte einiger Thermoelemente zwischen −200° und

+1000°C. (Double Neutral Points and Electromotive-force Values of Some Thermoelements between −200 and +1000°C.), *Ann. d. Physik*, ser. 4, v. 42, 1913, pp. 1504–1530.

106. KOWALKE, O. L.: Some Observations on Base-metal Thermocouples, *Trans. Am. Electrochem. Soc.*, v. 24, 1913, pp. 377–389. Abst.: *Met. Chem. Eng.*, v. 11, 1913, pp. 588–590.

107. WERNER, A.: Thermische Ausdehnung fester Körper bei höheren Temperaturen (Thermal Expansion of Solid Bodies at Elevated Temperatures), *Z. f. Dampfkessel u. Maschinenbetrieb*, v. 36, 1913, pp. 227–230.

108. ARNOLD, J. O., and A. A. READ: The Chemical and Mechanical Relations of Iron, Tungsten, and Carbon, and of Iron, Nickel, and Carbon, *Proc. Inst. Mech. Eng.*, 1914, parts 1–2, pp. 223–279 (248–267). Also: *Engineering*, v. 97, 1914, pp. 433–436, 468–470.

109. CHEVENARD, P.: Volumes spécifiques des aciers au nickel (Specific Volumes of Nickel Steels), *C. R. Acad. Sci.*, Paris, v. 159, 1914, pp. 53–56.

110. CHEVENARD, P.: Contribution à l'étude des aciers au nickel (Contribution to the Study of Nickel Steels), *Rev. de Mét., Mém.*, v. 11, 1914, pp. 841–862.

111. FROEHLICH, W.: "Über den Einfluss von Gasen auf hochprozentigen Nickelstahl" (The Effect of Gases on High-nickel Steel), Dissertation, Technische Hochschule, Berlin, 1914, 40 pp.

112. RUFF, O., and W. BORMANN: Arbeiten im Gebiete höherer Temperaturen.—V. Mangan und Kohlenstoff. VI. Nickel und Kohlenstoff. VII. Eisen und Kohlenstoff (High-temperature Investigations. V. Manganese and Carbon; VI. Nickel and Carbon; VII. Iron and Carbon), *Z. anorg. Chemie*, v. 88, 1914, pp. 365–385, 386–396, 397–409.

113. SCHÜBEL, P.: Wärmekapazität von Metallen und Metallverbindungen zwischen 18 und 600° (The Specific Heat of Metals and Metal Compounds between 18 and 600 deg. C.), *Z. anorg. Chemie*, v. 87, 1914, pp. 81–119.

114. SCHULZ, E. H.: Über die Volumen- und Formänderungen des Stahles beim Härten (Volume Change and Deformation of Steel upon Hardening), *Forschungsarb. a. d. Gebiete d. Ingenieurwesens*, No. 164, Verein deutscher Ingenieure, Berlin, 1914, 45 pp. Condensed: *Z. Ver. deutsch. Ing.*, v. 59, 1915, pp. 66–71, 112–116.

1915–1919

115. ABBOTT, R. R.: The Relation between Maximum Strength, Brinell Hardness, and Scleroscope Hardness in Treated and Untreated Alloy and Plain Steels, *Proc. Am. Soc. Test. Mat.*, v. 15, part 2, 1915, pp. 42–61.

116. DUPUY, E. L., and A. PORTEVIN: La thermo-électricité des aciers spéciaux (Thermoelectricity of Special Steels), *Rev. de Mét., Mém.*, v. 12, 1915, pp. 657–679. Also: *J. Iron Steel Inst.*, v. 91, 1915, pp 306–335.

117. FULLER, T. S.: The Thermoelectromotive Force of Certain Iron Alloys, *Trans. Am. Electrochem. Soc.*, v. 27, 1915, pp. 241–252.

118. GIEBELHAUSEN, H. VON: Über das Verhalten des Vanadins zu Silicium, Nickel, Kupfer und Silber und das Verhalten des Bors zu Nickel (The Reactions between Vanadium and Silicon, Nickel, Copper, and Silver and the Reactions between Boron and Nickel), *Z. anorg. Chemie*, v. 91, 1915, pp. 251–262.

119. TCHIJEVSKY, N. P., and S. MIKHAILOVSKY: Nickel-boron Steel, *Rev. Russian Met. Soc.*, v. 1, 1915, pp. 547–559. Abst.: *Rev. de Mét., Extraits*, v. 14, 1917, pp. 16–21.

120. BENEDICKS, C.: Om elektriska ledningsmotståndet hos järnets och andra metallers fasta lösningar (Electric Resistivity of the Solid Solutions of Iron and of Other Metals), *Jernk. Ann.*, v. 100 (71), 1916, pp. 35–60, 75.

121. GUILLAUME, CH.-ED.: Modifications de la dilatabilité de l'invar par des actions mécaniques ou thermiques (Modifications of the Dilatability of Invar through Thermal or Mechanical Effects), *C. R. Acad. Sci.*, Paris, v. 163, 1916, pp. 654–658. Abst.: *J. Soc. Chem. Ind.*, v. 36, 1917, p. 34.

122. STEAD, J. E.: Notes on Nickel Steel Scale and on the Reduction of Solid Nickel and Copper Oxides by Solid Iron, *J. Iron Steel Inst.*, v. 94, 1916, pp. 243–248.

123. WEISS, P., A. PICCARD, and A. CARRARD: Calorimétrie des substances ferro-magnétiques (Calorimetry of Ferromagnetic Substances), *Arch. Sci. Phys. et Nat.*, ser. 4, v. 42, 1916, pp. 378–401; v. 43, 1917, pp. 22–52.

124. ZIMMER, G. F.: The Use of Meteoric Iron by Primitive Man, *J. Iron Steel Inst.*, v. 94, 1916, pp. 306–356.

125. ABBOTT, R. R.: The Rôle of Nickel, *Proc. Am. Soc. Test. Mat.*, v. 17, part 2, 1917, pp. 9–14.

126. BENEDICKS, C.: Naturligt och syntetiskt meteor järn och deras elektricitetsledning (Natural and Synthetic Meteoric Irons and Their Electric Conductivity), *Jernk. Ann.*, v. 101 (72), 1917, pp. 58–67.

127. CAMPBELL, E. D.: Influence of Temperature of Measurement on the Electrical Resistivity and Thermo-electromotive Potential of Solutes in Steel, *Trans. Am. Electrochem. Soc.*, v. 32, 1917, pp. 193–214.

128. CHEVENARD, P.: Dilatomètre différentiel enregistreur. Description et premières applications (The Differential Dilatometer. Description and First Applications), *Rev. de Mét., Mém.*, v. 14, 1917, pp. 610–640.

129. GUILLAUME, CH.-ED.: Changement de la dilatation des alliages de fer et de nickel sous l'action de divers traitements thermiques ou mécaniques (Change of Dilatation of Iron-nickel Alloys through Different Thermal or Mechanical Treatments), *C. R. Acad. Sci.*, Paris, v. 164, 1917, pp. 904–906. Also: *Arch. Sci. Phys. et Nat.*, ser. 4, v. 45, 1918, pp. 407–417.

130. HONDA, K., and T. SIMIDU: On the Thermal and Electrical Conductivities of Carbon Steels at High Temperatures, *Sci. Rept.*, Sendai, ser. 1, v. 6, 1917, pp. 219–233.

131. HONDA, K., and H. TAKAGI: On the Cause of the Irreversibility of Nickel Steels, *Sci. Rept.*, Sendai, ser. 1, v. 6, 1917, pp. 321–340. Also: *J. Iron Steel Inst.*, v. 100, 1919, pp. 353–375.

132. HUNTER, M. A., and F. M. SEBAST: The Electrical Properties of Some High-resistance Alloys, *J. Am. Inst. Metals*, v. 11, 1917, pp. 115–138.

133. PFANN, E.: Über den inneren Gefügeaufbau der meteorischen Nickeleisen (Microstructure of Meteoric Nickel Irons), *Internationale Z. f. Metallographie*, v. 9, 1917, pp. 65–81.

134. DICKENSON, J. H. S.: Nickel-chromium Steels, *J. West of Scotland Iron Steel Inst.*, v. 26, 1918–1919, pp. 110–125; v. 27, 1919–1920, pp. 1–5.

135. ENLUND, B. D.: Om anvandbarheten av elektriska motstandsmatningar for undersökning av järn och stål (The Applicability of Electric-resistance Measurements in the Investigation of Iron and Steel), *Jernk. Ann.*, v. 102 (73), 1918, pp. 165–221.

136. GEBERT, N. J.: A Systematic Investigation of the Correlation of the Magnetic and Mechanical Properties of Steel, *J. Am. Steel Treat. Soc.*, v. 1, 1918–1919, pp. 302–311. Also: *Proc. Am. Soc. Test. Mat.*, v. 19, part 2, 1919, pp. 117–129.

137. HONDA, K.: On the Thermal and Electrical Conductivities of Nickel Steels, *Sci. Rept.*, Sendai, ser. 1, v. 7, 1918, pp. 59–66.

138. HUNTER, M. A., and J. W. BACON: Thermo-electromotive Force of Some Alloys, *Trans. Am. Electrochem. Soc.*, v. 33, 1918, pp. 183–196.

139. ÔKÔCHI, M., M. MAJIMA, and N. SATO: Molybdenum Steel versus Gun Erosion, *J. Coll. Eng.*, Tokyo Imp. Univ., v. 9, 1918, pp. 153–195.

140. WÜST, F., A. MEUTHEN, and R. DURRER: Die Temperatur-Wärmeinhaltskurven der technisch wichtigen Metalle (The Temperature versus Heat Content Curves of Technically Important Metals), *Forschungsarb. a. d. Gebiete d. Ingenieurwesens*, No. 204, Verein deutscher Ingenieure, Berlin, 1918, 60 pp.

141. CAMPBELL, E. D.: The Solution Theory of Steel and the Influence of Changes in Carbide Concentration on the Electrical Resistivity, *Trans. Faraday Soc.*, v. 15, 1919, pp. 138–149.

142. COHADE, J. J.: On the Woody Structures of Fractures of Transverse Test Pieces Taken from Certain Special Steels, *J. Iron Steel Inst.*, v. 100, 1919, pp. 187–201, 211–229.

143. HATFIELD, W. H.: The Most Suitable Steels for Automobile Parts, *Proc. Inst. Automobile Eng.*, v. 14, 1919–1920, pp. 503–600.

144. HONDA, K.: On the Moduli of Elasticity and Rigidity of Nickel Steels, *Sci. Rept.*, Sendai, ser. 1, v. 8, 1919, pp. 59–60.

1920

145. CHEVENARD, P.: Changement thermique des propriétés élastiques des aciers au nickel (Thermal Change of Elastic Properties of Nickel Steels), *C. R. Acad. Sci.*, Paris, v. 170, 1920, pp. 1499–1502.

146. GUILLAUME, CH.-ED.: L'élinvar, alliage à module d'élasticité invariable (Elinvar, an Alloy of Invariable Modulus of Elasticity), *Arch. Sci Phys. et Nat.*, ser. 5, v. 2, 1920, p. 413.

147. GUILLAUME, CH.-ED.: Cause de l'instabilité des aciers au nickel; son élimination (Cause of Instability of Nickel Steels; Its Elimination), *C. R. Acad. Sci.*, Paris, v. 171, 1920, pp. 1039–1041.

148. GUILLAUME, CH.-ED.: The Anomaly of the Nickel Steels, *Proc. Phys. Soc.*, London, v. 32, 1920, pp. 374–404.

149. HANSON, D., and H. E. HANSON: The Constitution of the Nickel-iron Alloys, *J. Iron Steel Inst.*, v. 102, 1920, pp. 39–64.

150. HOFFMANN, F., and A. SCHULZE: Über die Brauchbarkeit von Thermoelementen aus unedlen Leitern in hohen Temperaturen (The Applicability of Base-metal Thermocouples for High-temperature Measurements), *Elektrotechnische Z.*, v. 41, 1920, pp. 427–433.

151. HONDA, K., and K. KIDO: On the Change of Length of Magnetisation in Iron-nickel and Iron-cobalt Alloys, *Sci. Rept.*, Sendai, ser. 1, v. 9, 1920, pp. 221–231.

152. INGERSOLL, L. R., *et al.*: Some Physical Properties of Nickel-iron Alloys, *Physical Review*, ser. 2, v. 16, 1920; pp. 126–132.

153. MARBLE, W. H.: Stainless Steel: Its Treatment, Properties, and Application, *Trans. Am. Soc. Steel Treat.*, v. 1, 1920–1921, pp. 170–179.

154. REMINGTON, A. A., and J. H. S. DICKENSON, Chairmen: Report of the Steel Research Committee Founded by the Institution of Automobile Engineers and the Society of Motor Manufacturers and Traders on an Investigation Conducted to Establish the Mechanical Properties of the British Standard Wrought Automobile Steels, *Brit. Eng. Stand. Assoc. Report* 75, October, 1920, 72 pp.

155. RUER, R., and J. BIREN: Über die Löslichkeit des Graphits in geschmolzenem Eisen (Solubility of Graphite in Liquid Iron), *Z. anorg. allgem. Chemie*, v. 113, 1920, p. 98.

156. SCOTT, H.: Critical Ranges of Some Commercial Nickel Steels, *Bur. Stand. Sci. Papers*, v. 16, 1920, pp. 195–214. Also: *Trans. Am. Inst. Min. Met. Eng.*, v. 67, 1922, pp. 100–116.

157. YENSEN, T. D.: Magnetic and Electrical Properties of Iron-nickel Alloys, *J. Am. Inst. Elec. Eng.*, v. 39, 1920, pp. 396–405.

1921

158. ANDREWS, M. R.: X-ray Analysis of Three Series of Alloys, *Physical Review*, v. 18, 1921, pp. 245–254.

159. CALLOMON, C. B.: Method of Deoxidizing High-nickel Steel, *Foundry*, v. 49, 1921, p. 590.

160. CHEVENARD, P.: L'action des additions sur l'anomalie de dilatation des ferronickels; application aux alliages fer-nickel-chrome (Effect of Alloying Additions on Dilatation Anomaly of Iron-nickel Alloys; Application to Iron-nickel-chromium Alloys), *C. R. Acad. Sci.*, Paris, v. 172, 1921, pp. 594–596.

161. CHEVENARD, P.: Relation entre la dilatation anomale et la variation thermique de l'aimantation des corps ferromagnétiques (Relation

between the Anomalous Dilatation and the Variation with Temperature of Magnetization of Ferromagnetic Substances), *C. R. Acad. Sci.*, Paris, v. 172, 1921, pp. 1655–1657.

162. GUILLET, L.: Quelques essais aux chocs répétés (Repeated-impact Investigations), *Rev. de Mét., Mém.*, v. 18, 1921, pp. 96–100.

163. MACPHERRAN, R. S.: Comparative Tests of Steels at High Temperature, *Proc. Am. Soc. Test. Mat.*, v. 21, 1921, pp. 852–875.

164. MAURER, E., and W. SCHMIDT: Der Einfluss verschiedener Legierungsmetalle nebst Kohlenstoff auf einige physikalische Eigenschaften des Eisens (The Effect of Various Elements Including Carbon on Some Properties of Iron), *Mitt. K.-W. Inst. Eisenforschung*, v. 2, 1921, pp. 5–20.

165. OBATA, J.: The Effect of Magnetic Fields on Electrical Resistance of Some Alloys, *Res. Electrotech. Lab.*, Tokyo, No. 101, 1921, pp. 427–446. Also: (in English) "Nagaoka Anniversary Volume," Tokyo, 1925, pp. 219–239.

166. PEPE, A.: Sul potere termoelettrico delle leghe di acciaio e nichel (The Thermoelectric Potential of Nickel Steels), *Rend. Accad. Sci. Fisiche e Mat.*, Napoli, ser. 3a, v. 27, 1921, pp. 60–66.

167. PORTEVIN, A.: Sur la résistance électrique des aciers au nickel (Electric Resistivity of Nickel Steels), *C. R. Acad. Sci.*, Paris, v. 172, 1921, pp. 445–447.

168. PORTEVIN, A., and P. CHEVENARD: Remarques et observations concernant les phénomènes de trempe des aciers (Remarks and Observations Concerning the Quenching of Steel), *Rev. de Mét., Mém.*, v. 18, 1921, pp. 428–444.

169. SMITH, A. W.: Thermal, Electrical, and Magnetic Properties of Alloys, *J. Franklin Inst.*, v. 192, 1921, pp. 69–105, 157–202.

170. SPOONER, A. P.: Discussion of paper by R. S. MacPherran on Comparative Tests of Steels at High Temperatures, *Proc. Am. Soc. Test. Mat.*, v. 21, 1921, pp. 852–875 (863–868).

171. WELTER, G.: Elastizität und Festigkeit von Spezialstählen bei hohen Temperaturen (Elasticity and Strength of Special Steels at Elevated Temperature), *Forschungsarb. a. d. Gebiete d. Ingenieurwesens*, No. 230, Verein deutscher Ingenieure, Berlin, 1921, 67 pp.

1922

172. BROPHY, G. R.: Calite—A New Heat-resisting Alloy, *Trans. Am. Soc. Steel Treat.*, v. 2, 1922, pp. 384–386.

173. CHEVENARD, P.: Étude de la fragilité des ferronickels aux basses températures (Study of Brittleness of Iron-nickel Alloys at Low Temperatures), *Rev. de Mét., Mém.*, v. 19, 1922, pp. 209–214.

174. DICKENSON, J. H. S.: Some Experiments on the Flow of Steels at a Low Red Heat, with a Note on the Scaling of Heated Steels, *J. Iron Steel Inst.*, v. 106, 1922, pp. 103–154. Condensed: *Engineering*, v. 114, 1922, pp. 326–329, 339, 378–379.

175. EDERT, H.: Warmversuche mit Sonderstählen (High-temperature Tests on Alloy Steels), *Stahl u. Eisen*, v. 42, 1922, pp. 961–968.

176. GALIBOURG, J.: Utilisation de la force thermo-électromotrice de contact pour identifier quelques aciers (Using Thermal Electromotive Force for Identification of Some Steels), *C. R. Acad. Sci.*, Paris, v. 174, 1922, pp. 547–550.

177. HUNTER, M. A., and A. JONES: Some Electrical Properties of Alloys at High Temperatures, *Trans. Am. Electrochem. Soc.*, v. 42, 1922, pp. 159–180.

178. LAKE, E. F.: Cast Nickel-chromium Alloys, *Foundry*, v. 50, 1922, pp. 452–454.

179. MÜLLER, W.: Schlagbiegefestigkeit und Schlaghärte legierter Konstruktionsstähle (Impact Bending Strength and Impact Hardness of Alloy Structural Steels), *Forschungsarb. a. d. Gebiete d. Ingenieurwesens*, No. 247, Verein deutscher Ingenieure, Berlin, 1922, 38 pp.

180. SOUDER, W., and P. HIDNERT: Thermal Expansion of a Few Steels, *Bur. Stand. Sci. Papers*, No. 433, v. 17, 1922, pp. 611–626.

181. YENSEN, T. D.: Forgeability of Iron-nickel Alloys, *Trans. Am. Inst. Min. Met. Eng.*, v. 67, 1922, pp. 498–513.

1923

182. AITCHISON, L.: The Low Apparent Elastic Limit of Quenched or Work-hardened Steels, *Iron Steel Inst., Carnegie Schol. Mem.*, v. 12, 1923, pp. 113–217.

183. ANON.: Invar and Related Nickel Steels, *Bur. Stand. Circ.* 58, ed. 2, 1923, 93 pp.

184. ARNOLD, H. D., and G. W. ELMEN: Permalloy, an Alloy of Remarkable Magnetic Properties, *J. Franklin Inst.*, v. 195, 1923, pp. 621–632. Also: *Electrician*, v. 90, 1923, pp. 672–674.

185. ARNOLD, J. O.: The Correlation of the Chemical Constitutions of "True Steels" and Their Micrographic Structures, *J. Iron Steel Inst.*, v. 107, 1923, pp. 213–224.

186. FRENCH, H. J., and W. A. TUCKER: Strength of Steels at High Temperatures, *Iron Age*, v. 112, 1923, pp. 193–195, 275–278.

187. GUILLET, L., and M. BALLAY: Influence de l'écrouissage sur la résistivité des métaux et alliages (Effect of Cold Work on Electric Resistivity of Metals and Alloys), *Rev. de Mét., Mém.*, v. 20, 1923, pp. 398–408.

188. HANSON, D., and J. R. FREEMAN: The Constitution of the Alloys of Iron and Nickel, *J. Iron Steel Inst.*, v. 107, 1923, pp. 301–321.

189. HATFIELD, W. H.: The Influence of Nickel and Chromium upon the Solubility of Steel (in Relation to Corrosion), *J. Iron Steel Inst.*, v. 108, 1923, pp. 103–123.

190. KAYSER, J. F.: Heat- and Acid-resisting Alloys (Ni-Cr-Fe), *Trans. Faraday Soc.*, v. 19, 1923, pp. 184–195.

191. LANGENBERG, F. C.: Temperature and Charpy Impact Value, *Year Book Am. Iron Steel Inst.*, 1923, pp. 349–381. Condensed: *Iron Age*, v. 112, 1923, pp. 1170–1172.

192. McAdam, D. J., Jr.: Endurance Properties of Steel: Their Relation to Other Physical Properties and to Chemical Composition, *Proc. Am. Soc. Test. Mat.*, v. 23, part 2, 1923, pp. 56–105, 122.

193. McKeehan, L. W.: The Crystal Structure of Iron-nickel Alloys, *Physical Review*, ser. 2, v. 21, 1923, pp. 402–407.

194. Majo, E.: Influenza della tensione elastica sulla forza elettromotrice termoelettrica (The Effect of Elastic Stress on Thermal Electromotive Force), *Rend. Accad. Sci. Fisiche e Mat.*, Napoli, ser. 3a, v. 29, 1923, pp. 159–167.

1924

195. Aall, N. H.: Die Verschiebung des Perlitpunktes durch Nickel und Chrom (Effect of Nickel and Chromium on the Pearlite Point), *Stahl u. Eisen*, v. 44, 1924, pp. 256–259.

196. Anon.: Nickel and Its Alloys, *Bur. Stand. Circ.* 100, ed. 2, 1924, 162 pp.

197. Goerens, P.: Die Eigenschaften der Edelstähle (Properties of High-quality Steels), *Stahl u. Eisen*, v. 44, 1924, pp. 1645–1659.

198. Honda, K., and Y. Ôkubô: On the Measurement of the Coefficients of Thermal Expansion for Aluminum Alloys and Alloys of Nickel-iron and Cobalt-iron, *Sci. Rept.*, Sendai, ser. 1, v. 14, 1924, pp. 101–107.

199. Hunter, M. A., and A. Jones: Some Electrical Properties of High-resistance Alloys, *Trans. Am. Soc. Test. Mat.*, v. 24, part 2, 1924, pp. 401–415.

200. Johnson, J. B., and S. A. Christiansen: Characteristics of Material for Valves Operating at High Temperatures, *Proc. Am. Soc. Test. Mat.*, v. 24, part 2, 1924, pp. 383–400.

201. Jordan, H.: Die ferromagnetischen Konstanten für schwache Wechselfelder (Ferromagnetic Constants for Weak Alternating Fields), *Elektrische Nachrichten-Technik*, v. 1, 1924, pp. 7–29.

202. Klein, G.: Beiträge zur Kenntnis von Widerstandsmaterialien (Resistor Materials), *Elektrotechnische Z.*, v. 45, 1924, pp. 300–302.

203. McAdam, D. J., Jr.: Endurance Properties of Corrosion-resistant Steels, *Proc. Am. Soc. Test. Mat.*, v. 24, part 2, 1924, pp. 273–303.

204. Strauss, J., and J. W. Talley: Stainless Steels: Their Heat Treatment and Resistance to Sea-water Corrosion, *Proc. Am. Soc. Test. Mat.*, v. 24, part 2, 1924, pp. 217–258.

205. Utida, Y., and M. Saitô: The Oxidation of Metals and Alloys at High Temperatures, *Sci. Rept.*, Sendai, ser. 1, v. 13, 1924, pp. 391–399.

206. Vanick, J. S.: Deterioration of Some Metals in Hot Reducing Ammonia Gases, *Proc. Am. Soc. Test. Mat.*, v. 24, part 2, 1924, pp. 348–372.

1925

207. Anon.: A High-permeability Low-hysteresis Alloy, *J. Sci. Instruments*, v. 3, 1925–1926, pp. 24–25.

208. Benedicks, C., and P. Sederholm: L'anomalie de dilatation de l'invar (The Anomalous Dilatation of Invar), *Arkiv Mat. Astron. Fysik*, v.

19*B*, 1925, No. 1. Also: Benedicks: Meteoric Iron and Invar, in "Metallographic Researches," McGraw-Hill Book Company, Inc., New York, 1926, Chap. IV, pp. 99–150.

209. BUCKLEY, O. W., and L. W. McKEEHAN: Effect of Tension upon Magnetization and Magnetic Hysteresis in Permalloy, *Physical Review*, ser. 2, v. 26, 1925, pp. 261–273.

210. CAMPBELL, D. F.: A High-frequency Induction Furnace, *J. Iron Steel Inst.*, v. 112, 1925, pp. 69–77.

211. CHEVENARD, P.: Dispositifs simples pour mettre en évidence les transformations thermiques des aciers et les anomalies des alliages spéciaux (Simple Appliances for Demonstration of Thermal Transformations of Steels and of the Anomalies of Special Alloys), *Rev. de l'Industrie Minérale*, v. 50, 1925, part 1, pp. 107–130.

212. CHEVENARD, P., and A. PORTEVIN: Propriétés élastiques des alliages: Variation en fonction de la composition chimique (Elastic Properties of Alloys: Variation as Function of Chemical Composition), *C. R. Acad. Sci.*, Paris, v. 181, 1925, pp. 780–782.

213. GALIBOURG, J.: Thermo-électricité des métaux et alliages (Thermoelectricity of Metals and Alloys), *Rev. de Mét., Mém.*, v. 22, 1925, pp. 400–434, 527–538, 610–630.

214. GUMLICH, E.: Neuere Fortschritte in der Herstellung ferromagnetischer Stoffe (Recent Progress in the Production of Ferromagnetic Materials), *Z. tech. Physik*, v. 6, 1925, pp. 670–682.

215. KASÉ, T.: On the Equilibrium Diagram of the Iron-carbon-nickel System, *Sci. Rept.*, Sendai, ser. 1, v. 14, 1925, pp. 173–217.

216. KIMBALL, A. L., JR., and D. E. LOVELL: Variation of Young's Modulus with Temperature from Vibration Measurements, *Physical Review*, ser. 2, v. 26, 1925, pp. 121–124.

217. MAHOUX: Note sur les soupapes (Valves), *Rev. de Mét., Mém.*, v. 22, 1925, pp. 39–51.

218. MATHEWS, J. A.: Austenite and Austenitic Steels, *Trans. Am. Inst. Min. Met. Eng.*, v. 71, 1925, pp. 568–596.

219. MOORE, H. F., and T. M. JASPER: An Investigation of the Fatigue of Metals, University of Illinois, Eng. Exp. Sta., *Bull.* 152, Nov., 1925, (v. 19, 1924–1925), 89 pp.

220. National Physical Laboratory: "Tests on High-permeability Material," Report for the Year 1924, H. M. Stationery Office, London, 1925, 221 pp. (p. 88).

221. PESCHARD, M.: Contribution à l'étude des ferro-nickels (Contribution to the Study of Iron-nickel Alloys), *Rev. de Mét., Mém.*, v. 22, 1925, pp. 490–514, 581–609, 663–685. Also: *C. R. Acad. Sci.*, Paris, v. 180, 1925, pp. 1475–1478, 1836–1838; v. 181, 1925, pp. 99–101, 854–855.

222. RODEBUSH, W. H., and J. C. MICHALEK: The Atomic Heat Capacities of Iron and Nickel at Low Temperatures, *J. Am. Chem. Soc.*, v. 47, 1925, pp. 2117–2121.

223. SCHOFIELD, F. H.: The Thermal and Electrical Conductivities of Some Pure Metals, *Proc. Royal Soc.*, London, ser. A, v. 107, 1925, pp. 206–227.

224. UTIDA, Y., and M. SAITÔ: The Influence of Metallic Elements on the Corrosion of Iron and Steel, *Sci. Rept.*, Sendai, ser. 1, v. 14, 1925, pp. 295–312.

225. VOGEL, R.: Über die Struktur der Eisen-Nickelmeteoriten (The Structure of Iron-nickel Meteorites), *Z. anorg. allgem. Chemie*, v. 142, 1925, pp. 193–228.   Condensed: *Archiv f. d. Eisenhüttenwesen*, v. 1, 1927, pp. 605–611.

226. WÜRSCHMIDT, J.: Die magnetischen Eigenschaften der Nickelstähle (Magnetic Properties of Nickel Steels), *Kruppsche Monatshefte*, v. 6, 1925, pp. 182–184, 226–232, 241–248.

227. YENSEN, T. D.: Magnetic Properties of the Fifty Per Cent Iron-nickel Alloys, *J. Franklin Inst.*, v. 199, 1925, pp. 333–342.

1926

228. ANDREW, J. H., and H. A. DICKIE: A Physical Investigation into the Cause of Temper Brittleness, *J. Iron Steel Inst.*, v. 114, 1926, pp. 359–395.

229. BENEDICKS, C., H. BÄCKSTRÖM, and P. SEDERHOLM: Anomalies in Heat Conduction as Investigated in Spherical Specimens, with Some Determinations of Thermal Conductivity in Iron and Carbon Steels, *J. Iron Steel Inst.*, v. 114, 1926, pp. 127–175.

230. BLOMQVIST, E. A.: An Investigation of the Physical Properties of Some Nickel-iron Alloys of the Invar Group, *Rensselaer Polytechnic Inst.*, *Eng. Sci. Ser.*, No. 13, 1926, 14 pp.

231. CHEVENARD, P.: Allure des isothermes représentant la résistivité et le pouvoir thermo-électrique des ferronickels réversibles, dans l'interval −200° à +1000° (The Behavior of the Isotherms Representing Resistivity and Thermoelectric Power of Reversible Iron-nickel Alloys over the Interval from −200 to +1000°C.), *C. R. Acad. Sci.*, Paris, v. 182, 1926, pp. 1388–1391.

232. HONDA, K., and T. TANAKA: On the Moduli of Elasticity and Rigidity, and Their Change Caused by Magnetization, in Different Kinds of Steel, *Sci. Rept.*, Sendai, ser. 1, v. 15, 1926, pp. 1–37.

233. KAWAKAMI, M.: On the Specific Heat of Iron-nickel Alloys, *Sci. Rept.*, Sendai, ser. 1, v. 15, 1926, pp. 251–262.

234. KERNS, R. S.: Melt High-chromium Alloys in Acid Furnace, *Foundry*, v. 54, 1926, pp. 229–231.

235. KLINKHARDT, H.: Eine neue Methode zur Bestimmung wahrer spezifischer Wärmen bei hohen Temperaturen (A New Method for Determination of True Specific Heats at High Temperatures), *Z. f. Elektrochemie*, v. 32, 1926, pp. 534–536.

236. MASUMOTO, H.: On a New Transformation of Cobalt and the Equilibrium Diagrams of Nickel-cobalt and Iron-cobalt, *Sci. Rept.*, Sendai, ser. 1, v. 15, 1926, pp. 449–477.

237. McKEEHAN, L. W.: Magnetostriction, *J. Franklin Inst.*, v. 202, 1926, pp. 737–773.

238. McKEEHAN, L. W.: The Significance of Magnetostriction in Permalloy, *Physical Review*, ser. 2, v. 28, 1926, pp. 158–166.

239. McKeehan, L. W., and P. P. Cioffi: Magnetostriction in Permalloy, *Physical Review*, ser. 2, v. 28, 1926, pp. 146–157.

240. Osawa, A.: The Relation between Space Lattice and Density of Iron-nickel Alloys, *Sci. Rept.*, Sendai, ser. 1, v. 15, 1926, pp. 386–398. Also: *J. Iron Steel Inst.*, v. 113, 1926, pp. 447–456.

241. Ribbeck, F.: Über die Abhängigkeit des elektrischen Widerstandes der Nickelstähle von Zusammensetzung, Temperatur und Wärmebehandlung (Dependence of Electric Resistivity of Nickel Steels on Composition, Temperature, and Heat Treatment), *Z. f. Physik*, v. 38, 1926, pp. 772–787, 887–907; v. 39, 1926, pp. 787–812.

242. Rohn, W.: Säurefeste Legierungen mit Nickel als Basis (Acid-resistant Nickel-base Alloys), *Z. f. Metallkunde*, v. 18, 1926, pp. 387–399.

243. Saffy, J. F.: Influence d'un séjour prolongé au rouge sur la résilience de quelques métaux pour soupapes d'échappement (Effect of Prolonged Exposure to Red Heat on the Impact Resistance of Some Metals Used for Exhaust Valves), *C. R. Acad. Sci.*, Paris, v. 183, 1926, pp. 861–863.

244. Scheil, E.: Zur Frage der Stabilität des Eisencarbides bei höherem Druck (Stability of Iron Carbide at High Pressure), *Z. anorg. allgem. Chemie*, v. 158, 1926, pp. 175–180.

245. Schottky, H., and F. Stäblein: Über das Gleichgewichtsschaubild des Systems Eisen-Kohlenstoff-Nickel (The Equilibrium Diagram of the Iron-nickel-carbon System), *Stahl u. Eisen*, v. 46, 1926, pp. 1796–1798.

246. Spooner, T.: Current Transformers with Nickel-iron Cores, *J. Am. Inst. Elec. Eng.*, v. 45, 1926, pp. 540–545.

247. Thompson, J. G.: Materials of Construction for Nitrogen Fixation, *Trans. Am. Electrochem. Soc.*, v. 50, 1926, pp. 101–116.

248. Yamada, R.: On the Impact Test of Steels at Low Temperatures, *Sci. Rept.*, Sendai, ser. 1, v. 15, 1926, pp. 631–659.

1927

249. Bain, E. C., and W. E. Griffiths: An Introduction to the Iron-chromium-nickel Alloys, *Trans. Am. Inst. Min. Met. Eng.*, v. 75, 1927, pp. 166–213.

250. Chevenard, P.: Recherches expérimentales sur les alliages de fer, de nickel et de chrome (Experimental Investigations of Iron-nickel-chromium Alloys), *Trav. Mém. Bur. International des Poids et Mesures*, v. 17, 1927, 144 pp.

251. Dickie, H. A.: Magnetic and Other Changes Concerned in the Temper Brittleness of Ni-Cr Steels, *J. Iron Steel Inst.*, v. 116, 1927, pp. 223–243.

252. Everest, A. B., T. H. Turner, and D. Hanson: The Influence of Nickel and Silicon on an Iron-carbon Alloy, *J. Iron Steel Inst.*, v. 116, 1927, pp. 185–221.

253. French, H. J., H. C. Cross, and A. A. Peterson: Creep in Five Steels at Different Temperatures, *Bur. Stand. Tech. Papers*, v. 22, 1927–1928, pp. 235–267.

254. GUILLAUME, CH.-ED.: Recherches métrologiques sur les aciers au nickel (Metrologic Researches on Nickel Steels), *Trav. Mém. Bur. International des Poids et Mesures*, v. 17, 1927, 240 pp.

255. HATFIELD, W. H.: Heat-resisting Steels, *J. Iron Steel Inst.*, v. 115, 1927, pp. 483–522.

256. HONDA, K., and S. MIURA: On the Determination of the Heterogeneous Field in the System Iron-nickel, *Sci. Rept.*, Sendai, ser. 1, v. 16, 1927, pp. 745–753. Also: *Trans. Am. Soc. Steel Treat.*, v. 13, 1928, pp. 270–281.

257. HOUDREMONT, E., and E. BURKLIN: Volumenänderungen von Stahl beim Kaltrecken (Volume Changes in Steel in Cold Drawing), *Stahl u. Eisen*, v. 47, 1927, pp. 90–93.

258. HOUDREMONT, E., and H. KALLEN: Die Formänderungsfähigkeit verschieden legierter Stähle in der Wärme (Formability of Various Alloy Steels at Elevated Temperatures), *Stahl u. Eisen*, v. 47, 1927, pp. 826–836.

259. JUNG, A. O.: Die Raumgitterstruktur und Gitterkonstanten des künstlichen und natürlichen Nickeleisens (The Lattice Structure and Lattice Constants of Artificial and Natural Nickel-iron Alloys), *Z. f. Kristallographie*, v. 65, 1927, pp. 309–334. Abst.: *Chem. Abst.*, v. 21, 1927, p. 3775. Abst.: *J. Inst. Met.*, v. 42, 1929, p. 514.

260. KASÉ, T.: On the Equilibrium Diagram of the Iron-cobalt-nickel System, *Sci. Rept.*, Sendai, ser. 1, v. 16, 1927, pp. 491–513.

261. KAYSER, J. F.: The Production and Uses of Ni-Cr-Fe and Co-Cr-Fe Castings, *Foundry Tr. J.*, v. 35, 1927, pp. 351–354. Also: *Iron Coal Tr. Rev.*, v. 115, 1927, pp. 202–203.

262. McADAM, D. J., JR.: Corrosion Fatigue of Metals as Affected by Chemical Composition, Heat Treatment, and Cold Working, *Trans. Am. Soc. Steel Treat.*, v. 11, 1927, pp. 355–390.

263. MACPHERRAN, R. S.: Some Tests of a Chrome-nickel Steel at High Temperatures, *Proc. Am. Soc. Test. Mat.*, v. 27, part 2, 1927, pp. 73–77.

264. MASUMOTO, H., and S. NARA: On the Coefficient of Thermal Expansion in Nickel-cobalt and Iron-cobalt Alloys, and the Magnetostriction of Iron-nickel Alloys, *Sci. Rept.*, Sendai, ser. 1, v. 16, 1927, pp. 333–341.

265. ROHN, W.: Vergleichende Untersuchungen über die Oxydation von Chromnickellegierungen bei hohen Temperaturen (Comparative Oxidation of Chromium-nickel Alloys at High Temperatures), *Elektrotechnische Z.*, v. 48, 1927, pp. 227–230, 317–320.

266. SCHULZE, A.: Die thermische Ausdehnung der Kobalt-Nickel, Kobalt-Eisen und Eisen-Nickel Legierungen (Thermal Expansion of Cobalt-nickel, Cobalt-iron, and Iron-nickel Alloys), *Physikalische Z.*, v. 28, 1927, pp. 669–673.

267. SUTTON, R.: A Study of Some of the Causes of Failure in Heat-resisting Alloys, *Trans. Am. Soc. Steel Treat.*, v. 12, 1927, pp. 221–234.

268. UMINO, S.: On the Heat of Transformation of Nickel and Cobalt, *Sci. Rept.*, Sendai, ser. 1, v. 16, 1927, pp. 593–609.

1928

269. BRIDGMAN, P. W.: The Effect of Pressure on the Resistance of Three Series of Alloys, *Proc. Am. Acad. Arts Sci.*, v. 63, 1928, pp. 329–345.

270. CHEVENARD, P.: Les alliages à hautes teneurs en nickel et en chrome (High-nickel, High-chromium Alloys), *Rev. de Mét., Mém.*, v. 25, 1928, pp. 14–34.

271. CHEVENARD, P.: Der Einfluss eines Chromzusatzes auf die elektrischen Eigenschaften der Eisen-Nickel-Legierungen (Effect of Chromium Addition on the Electric Properties of Iron-nickel Alloys), *Stahl u. Eisen*, v. 48, 1928, pp. 1045–1049. Also: *C. R. Acad. Sci.*, Paris, v. 186, 1928, pp. 431–433.

272. ELMEN, G. W.: Magnetic Properties of Perminvar, *J. Franklin Inst.*, v. 206, 1928, pp. 181–200.

273. ENDO, H.: The Corrosion of Steel by Acid Solutions, *Sci. Rept.*, Sendai, ser. 1, v. 17, 1928, pp. 1245–1263.

274. GUERTLER, W., and W. ACKERMANN: Einige Versuche über Säurebeständigkeit reinster Chrom-Nickel-Eisenlegierungen (Some Experiments on the Acid Resistance of Very Pure Iron-chromium-nickel Alloys), *Z. f. Metallkunde*, v. 20, 1928, pp. 269–279.

275. GUILLAUME, CH.-ED.: Les anomalies des aciers au nickel et leurs applications (The Anomalies of Nickel Steels and Their Uses), *Rev. de Mét., Mém.*, v. 25, 1928, pp. 35–43.

276. GUMLICH, E., W. STEINHAUS, A. KUSSMANN, and B. SCHARNOW: Über Materialien mit hoher Anfangspermeabilität.—I. Mitteilung (Materials of High Initial Permeability.—I.), *Elektrische Nachrichten-Technik*, v. 5, 1928, pp. 83–100.

277. HATFIELD, W. H.: Heat-resisting Steels—Part 2: Mechanical Properties, *J. Iron Steel Inst.*, v. 117, 1928, pp. 573–610.

278. HATFIELD, W. H.: The Response of Steels at Elevated Temperature, *J. West of Scotland Iron Steel Inst.*, v. 36, 1928–1929, pp. 60–70.

279. KÖTZSCHKE, P., and E. PIWOWARSKY: Über die Korrosion und das Rosten von unlegiertem und legiertem Gusseisen (Corrosion and Rusting of Unalloyed and Alloy Cast Irons), *Archiv f. d. Eisenhüttenwesen*, v. 2, 1928–1929, pp. 333–340. Abst.: *Korrosion u. Metallschutz*, v. 5, 1929, pp. 174–176. Condensed: *Foundry*, v. 57, 1929, pp. 863–866.

280. LAPP, C.: Mesure des chaleurs spécifiques vraies du nickel par une méthode électrique directe (Determination of the True Specific Heats of Nickel by a Direct Electrical Method), *C. R. Acad. Sci.*, Paris, v. 186, 1928, pp. 1104–1106. Also: *Ann. de Physique*, v. 12, 1929, pp. 442–521.

281. McKNIGHT, C.: Alloy Steel for Boiler Construction, *Trans. Am. Soc. Steel Treat.*, v. 13, 1928, pp. 638–658.

282. McVETTY, P. G.: Testing of Materials at Elevated Temperatures, *Proc. Am. Soc. Test. Mat.*, v. 28, part 2, 1928, pp. 60–79.

283. MEHL, R. F.: Interatomic Forces in Metals and Alloys, *Trans. Am. Inst. Min. Met. Eng.*, v. 78, 1928, pp. 405–428.

284. NEUMANN, W.: Magnetische Hysteresis bei hoher Frequenz (Magnetic Hysteresis at High Frequency), *Z. f. Physik*, v. 51, 1928, pp. 355–373.

285. PIERCE, G. W.: Magnetostriction Oscillators, *Proc. Am. Acad. Arts Sci.*, v. 63, 1928, pp. 1–47.

286. SCHULZE, A.: Magnetostriktion.—I. (Magnetostriction.—I.), *Z. f. Physik*, v. 50, 1928, pp. 448–505. Discussion by L. W. McKeehan, *ibid.*, v. 52, 1928–1929, pp. 752–754. Prel.: *Archiv f. Elektrotechnik*, v. 18, 1927, pp. 683–692. Also: *Z. tech. Physik*, v. 8, 1927, pp. 495–502.

287. SCOTT, H.: Expansion Characteristics of Low-expansion Nickel Steels, *Trans. Am. Soc. Steel Treat.*, v. 13, 1928, pp. 829–847.

288. SHACKELTON, W. J., and I. G. BARBER: Compressed Powdered Permalloy. Manufacture and Magnetic Properties, *J. Am. Inst. Elec. Eng.*, v. 47, 1928, pp. 437–440.

1929

289. AKULOV, N. S.: Über ein Gesetz, das verschiedene Eigenschaften ferromagnetischer Kristalle miteinander verknüpft (A Correlation of Various Properties of Ferromagnetic Crystals), *Z. f. Physik*, v. 59, 1929–1930, pp. 254–264.

290. ANDREW, J. H., and D. BINNIE: The Liquidus and Solidus Range of Some Commercial Steels. Section 2 of Third Report on Heterogeneity of Steel Ingots, *J. Iron Steel Inst.*, v. 119, 1929, pp. 309–346.

291. BENEDICKS, C., N. ERICSSON, and G. ERICSON: Bestämning av specifika volumet för järn, nickel och järnlegeringar i smält tillstånd (Determination of the Specific Volume of Iron, Nickel, and Iron Alloys in the Molten Condition), *Jernk. Ann.*, v. 113 (86), 1929, pp. 423–490. Also: *Archiv f. d. Eisenhüttenwesen*, v. 3, 1929–1930, pp. 473–486.

292. CHEVENARD, P. A., A. M. PORTEVIN, and X. F. WACHÉ: A Dilatometric Study of Some Univariant Two-phase Reactions, *J. Inst. Metals*, v. 42, 1929, pp. 337–373.

293. CLARK, C. L., and A. E. WHITE: The Stability of Metals at Elevated Temperatures, *Trans. Am. Soc. Steel Treat.*, v. 15, 1929, pp. 670–714.

294. CORFIELD, J. D.: Heat-resisting Alloys and Their Use in the Steel Plant, *Iron Steel Eng.*, v. 6, 1929, pp. 157–162.

295. DICKIE, H. A.: The Solubility of Carbide in Ferrite, *J. Iron Steel Inst.*, v. 120, 1929, pp. 161–185.

296. EARNSHAW, W. B.: Weak Sulphuric Acid Yields to Nickel-silicon Steels, *Chem. Met. Eng.*, v. 36, 1929, p. 536.

297. ELMEN, G. W.: Magnetic Alloys of Iron, Nickel, and Cobalt, *J. Franklin Inst.*, v. 207, 1929, pp. 583–617. Also: *Bell System Tech. J.*, v. 8, 1929, pp. 435–465.

298. FIELD, B. E.: New Alloys Withstand Hydrochloric Acid, *Chem. Met. Eng.*, v. 36, 1929, p. 542.

299. FIELD, B. E.: Some New Developments in Acid-resistant Alloys, *Trans. Am. Inst. Min. Met. Eng.*, v. 83, 1929, pp. 149–159.

300. FINK, C. G., and C. M. DeCROLY: The Corrosion Rate of Ferronickel Alloys, *Trans. Am. Electrochem. Soc.*, v. 56, 1929, pp. 239–277.

301. GOSSELS, G.: Versuche über die Stabilität der Hysteresis Fe-Ni Legierungen (Experiments Concerning the Stability of the Hysteresis Fe-Ni Alloys), *Z. anorg. allgem. Chemie*, v. 182, 1929, pp. 19–27.

302. GREULICH, E., and G. BEDESCHI: Technologische und metallographische Eigenschaften eines hochlegierten Chrom-Nickel-Stahles (Technological and Metallographic Properties of a High Chrome-nickel Steel), *Archiv f. d. Eisenhüttenwesen*, v. 3, 1929–1930, pp. 349–363.

303. HATFIELD, W. H.: Acid-resisting Steels, *Metallurgia*, v. 1, 1929, pp. 17–20, 26.

304. HATFIELD, W. H.: The Application of Science to the Steel Industry, *Trans. Am. Soc. Steel Treat.*, v. 15, 1929, pp. 474–502, 652–669, 817–836, 986–1026; v. 16, 1929, pp. 121–154, 278–292.

305. HOUDREMONT, E., and V. EHMCKE: Warmfeste Stähle (Heat-resistant Steels), *Archiv f. d. Eisenhüttenwesen*, v. 3, 1929–1930, pp. 49–60. Also: *Kruppsche Monatshefte*, v. 10, 1929, pp. 79–94.

306. KROLL, W.: Die Legierungen des Berylliums mit Eisen (Iron-beryllium Alloys), *Wiss. Veröffentl. a. d. Siemens-Konzern*, v. 8, 1929, No. 1, pp. 220–235. Also, translated, in R. Rimbach and A. J. Michel: "Beryllium—Its Production and Application," The Chemical Catalog Company, Inc., New York, 1932, pp. 280–299.

307. KUSSMANN, A., and B. SCHARNOW: Über die Koerzitivkraft.—I. Teil: Koerzitivkraft und mechanische Härte (Coercive Force.—I. Coercive Force and Mechanical Hardness), *Z. f. Physik*, v. 54, 1929, pp. 1–15.

308. MASUMOTO, H.: On the Intensity of Magnetization in Iron-nickel-cobalt Alloys, *Sci. Rept.*, Sendai, ser. 1, v. 18, 1929, pp. 195–229.

309. MAURER, E., and K. SCHROETER: Die Bestimmung des Austenitgehaltes durch Messung des magnetischen Sättigungswertes und die Vorgänge beim Anlassen gehärteter Stähle (Determination of Austenite Content by Measuring the Magnetic Saturation and the Reactions upon Tempering of Hardened Steels), *Stahl u. Eisen*, v. 49, 1929, pp. 929–940.

310. MENOUGH, P. S.: Properties of Corrosion-resisting Alloys, *Blast Furnace and Steel Plant*, v. 17, 1929, pp. 1648–1651, 1655, 1810–1815. Also: *Heat Treat. and Forging*, v. 15, 1929, pp. 1437–1440, 1450, 1567–1572.

311. MERZ, A.: Der Einfluss verschiedener Legierungselemente auf die kritischen Punkte von Kohlenstoffstahl (The Influence of Various Alloying Elements on the Critical Points of Carbon Steel), *Archiv f. d. Eisenhüttenwesen*, v. 3, 1929–1930, pp. 587–596.

312. NISHIYAMA, Z.: On the Measurement of the Elastic Constant, Lattice Constant, and Density of Binary Alloys in the Range of Solid Solution, *Sci. Rept.*, Sendai, ser. 1, v. 18, 1929, pp. 359–400.

313. NORTON, F. H.: "The Creep of Steel at High Temperatures," McGraw-Hill Book Company, Inc., New York, 1929, 90 pp.

314. PETTORINO, A.: Sulla variazione della forza elettromotrice termoelettrica per influenza del magnetismo trasversale (The Effect of a Transverse Magnetic Field on Thermal Electromotive Force), *Rend. Accad. Sci. Fisiche e Mat.*, Napoli, ser. 4a, v. 35, 1929, pp. 256–261.

315. PFEIL, L. B.: The Oxidation of Iron and Steel at High Temperature, *J. Iron Steel Inst.*, v. 119, 1929, pp. 501–560.

316. PILLING, N. B., and D. E. ACKERMAN: Resistance of Iron-nickel-chromium Alloys to Corrosion by Acids, *Trans. Am. Inst. Min. Met. Eng.*, v. 83, 1929, pp. 248–279.

317. PREISACH, F.: Untersuchungen über den Barkhauseneffekt (Investigations of the Barkhausen Effect), *Ann. d. Physik*, ser. 5, v. 3, 1929, pp. 737–799.

318. RAFFO, M.: Studio di una ferro lega usata in un impianto di ammoniaca sintetica (Investigation of an Iron Alloy Used in a Synthetic Ammonia Plant), *Metallurgia Italiana*, v. 21, 1929, pp. 213–219.

319. RUSSELL, T. F.: Low-expansion Nickel Steel, *Engineering*, v. 128, 1929, pp. 400–402.

320. SCHENCK, P. D.: Metals and Alloys with Resistance to Sulphates and Sulphuric Acid, *Chem. Met. Eng.*, v. 36, 1929, pp. 575–576.

321. SCHICHTEL, K., and E. PIWOWARSKY: Über den Einfluss der Legierungselemente Phosphor, Silizium und Nickel auf die Löslichkeit des Kohlenstoffs im flüssigen Eisen (The Influence of the Alloying Elements Phosphorus, Silicon, and Nickel on the Solubility of Carbon in Liquid Iron), *Archiv f. d. Eisenhüttenwesen*, v. 3, 1929–1930, pp. 139–147.

322. SCHMITZ, F.: Über die Widerstandsfähigkeit einiger Stähle gegenüber chemischen Einflüssen in Abhängigkeit von Kohlenstoff-, Nickel- und Chrom-Gehalt (Effect of Carbon, Nickel, and Chromium Contents on the Resistance of Some Steels to Chemical Attack), *Z. f. Metallkunde*, v. 21, 1929, pp. 64–65.

323. SIMONDS, H. R.: Alloy Castings to Withstand Severe Service, *Foundry*, v. 57, 1929, pp. 180–183.

324. SIZOO, G. J., and C. ZWIKKER: Zur Kenntnis des Systems Nickel-Eisen (The Nickel-iron System), *Z. f. Metallkunde*, v. 21, 1929, pp. 125–126.

325. SMITH, A. W., and J. DILLINGER: The Effect of Tension and a Longitudinal Magnetic Field on the Thermo-electromotive Forces in Permalloy, *Physical Review*, ser. 2, v. 33, 1929, pp. 389–402.

326. TAPSELL, H. J., and J. REMFRY: The "Creep" Strength of a "High-nickel, High-chromium Steel" between 600°C. and 800°C., *Dept. Sci. Ind. Research, Eng. Research, Special Rept.* 15, H. M. Stationery Office, London, 1929, 7 pp.

327. TASAKI, M. Über die ternären Systeme Fe-Cu-Ni und Fe-Cr-Ni (The Ternary Systems Iron-copper-nickel and Iron-chromium-nickel), World Eng. Congress, Tokyo, 1929, *Proc.*, v. 36, Min. Met., part 4, pp. 231–245.

328. Vogel, R., and W. Tonn: Über das ternäre System Eisen-Nickel-Schwefel (The Ternary System Iron-nickel-sulphur), *Archiv f. d. Eisenhüttenwesen*, v. 3, 1929–1930, pp. 769–780.

1930

329. Akulov, N. S.: Über die Anwendungen des Gesetzes ferromagnetischer Anisotropie zur Berechnung der Eigenschaften polykristallinischen Eisens (Using the Law of Ferromagnetic Anisotropy for Computation of the Properties of Polycrystalline Iron), *Z. f. Physik*, v. 66, 1930, pp. 533–542.

330. Auwers O. von: Über die magnetischen Eigenschaften von Permalloy mit inneren Spannungen und ihre Beeinflussung durch äusseren Zug und Druck (The Magnetic Properties of Permalloy with Internal Stresses and the Effect of Tension and Compression Thereon), *Wiss. Veröffentl. a. d. Siemens-Konzern*, v. 9, 1930, No. 2, pp. 262–293.

331. Ballay, M.: Les applications du nickel dans les industries électriques (Uses of Nickel in the Electric Industries), International Congress Min. Met., Liége, June, 1930, v. 3, pp. 471–492. Also: *Revue du Nickel*, 1930, pp. 127–135; 1931, pp. 2–15. Also: *Houille Blanche*, v. 30, 1931, pp. 144–152, 166–176.

332. Boegehold, A. L.: Present-day Methods in Production and Utilization of Automotive Cast Iron, in "Symposium on Developments in Automotive Materials," American Society for Testing Materials, Philadelphia, 1930, pp. 1–17.

333. Cazaud, R.: Application de la thermo-électricité à l'étude et au controle des produits métallurgiques au moyen de l'appareil J. Galibourg (Application of Thermoelectricity to the Study and Testing of Metallurgical Products by Means of J. Galibourg's Apparatus), *Aciers Spéciaux*, v. 5, 1930, pp. 110–113.

334. Courtois, G.: Quelques idées générales sur le chauffage électrique (Some General Ideas on Electric Heating), *Science et Industrie*, v. 14, 1930, pp. 921–924.

335. Dean, W. A.: An Investigation of Some of the Physical Properties of the Iron-nickel-chromium System, *Rensselaer Polytechnic Inst., Eng. Sci. Ser.*, No. 26, 1930, pp. 31–35.

336. Eucken, A., and H. Werth: Die spezifische Wärme einiger Metalle und Metallegierungen bei tiefen Temperaturen (The Specific Heat of Some Metals and Metal Alloys at Low Temperatures), *Z. anorg. allgem. Chemie*, v. 188, 1930, pp. 152–172.

337. Fischer, F. K.: An Investigation of the Magnetic and Electrical Properties of Some Iron-chromium Alloys, *Rensselaer Polytechnic Inst., Eng. Sci. Ser.*, No. 28, 1930, 32 pp.

338. French, H. J., W. Kahlbaum, and A. A. Peterson: Flow Characteristics of Special Fe-Ni-Cr Alloys and Some Steels at Elevated Temperatures, *Bur. Stand. J. Research*, v. 5, 1930, pp. 125–183.

339. GROSSMANN, M. A.: Alloys of Iron, Nickel, and Chromium, *First Communications of the New Int. Assoc. Test. Mat.*, 1930, Group A, pp. 97–103.

340. GRUBER, H.: "Das Verhalten hitzebeständiger Legierungen gegen Schwefel und eine neue schwefelbeständige Legierung" (The Behavior of Heat-resistant Alloys toward Sulphur and a New Sulphur-resistant Alloy), Festschrift z. 70. Geburtstage v. W. Heraeus, Hanau, 1930, pp. 45–51. Reprint: *Z. f. Metallkunde*, v. 23, 1931, pp. 151–157.

341. GÜMLICH, E., W. STEINHAUS, A. KUSSMANN, and B. SCHARNOW: Über Materialien mit hoher Anfangspermeabilität.—II. Mitteilung (Materials of High Initial Permeability.—II.), *Elektrische Nachrichten-Technik*, v. 7, 1930, pp. 231–235.

342. HENDRICKS, S. B., N. E. JEFFERSON, and J. F. SCHULTZ: The Transition Temperatures of Cobalt and Nickel; Some Observations on Oxides of Nickel, *Z. f. Kristallographie*, v. 73, 1930, pp. 376–380.

343. HONDA, K.: On the Cause of the High Permeability in the Air-quenched Permalloy, *Sci. Rept.*, Sendai, ser. 1, v. 19, 1930, pp. 731–735. Also: *Z. f. Physik*, v. 67, 1931, pp. 808–811.

344. HOUDREMONT, E.: Die rostfreien Stähle, ihre Erzeugung und ihre Eigenschaften (Stainless Steels, Their Manufacture and Properties), *Stahl u. Eisen*, v. 50, 1930, pp. 1517–1528. Also: *Kruppsche Monatshefte*, v. 11, 1930, pp. 270–286. Also: *Rev. de Mét., Mém.*, v. 28, 1931, pp. 40–59. Critical abst.: *Metals & Alloys*, v. 2, 1931, pp. 31–33.

345. JARDINE, F.: Thermal Expansion in Automotive Engine Design, *J. Soc. Automotive Eng.*, v. 27, 1930, pp. 311–319.

346. JENKINS, C. H. M., H. J. TAPSELL, C. R. AUSTIN, and W. P. REES: Some Alloys for Use at High Temperatures. Nickel-chromium and Complex Iron-nickel-chromium Alloys, *J. Iron Steel Inst.*, v. 121, 1930, pp. 237–314.

347. JOHNSON, C. M.: Corrosion- and Heat-resisting Steels as Applied to Automobile and Bus Use, in "Symposium on Developments in Automotive Materials," American Society for Testing Materials, Philadelphia, 1930, pp. 28–53. Also: *Metals & Alloys*, v. 1, 1930, pp. 547–553.

348. JORDAN, L., and W. H. SWANGER: Properties of Pure Nickel, *Bur. Stand. J. Research*, v. 5, 1930, pp. 1291–1307, 1309.

349. KAWAI, T.: The Effect of Cold Working on Young's Modulus of Elasticity, *Sci. Rept.*, Sendai, ser. 1, v. 19, 1930, pp. 209–234.

350. KOSTING, P. R.: The Nickel-iron-copper System, *Rensselaer Polytechnic Inst., Eng. Sci. Ser.*, No. 26, 1930, pp. 1–27.

351. KROLL, W.: Vergütbare Titan-Legierungen (Titanium Alloys Responding to Heat Treatment), *Metallwirtschaft*, v. 9, 1930, pp. 1043–1045.

352. KÜHLEWEIN, H.: Die Legierungen des ternären Systems Eisen-Nickel-Kobalt (The Ternary Iron-nickel-cobalt Alloys), *Physikalische Z.*, v. 31, 1930, pp. 626–640.

353. Losana, L.: Corrosione degli acciai ad elevate temperature (Corrosion of Steels at Elevated Temperature), *Industria Chimica*, v. 5, 1930, pp. 288–291, 565–571.

354. McKeehan, L. W.: Electrical Resistance of Nickel and Permalloy Wires as Affected by Longitudinal Magnetization and Tension, *Physical Review*, ser. 2, v. 36, 1930, pp. 948–977.

355. Merrill, G. P.: Composition and Structure of Meteorites, Smithonian Inst., U. S. National Museum, *Bull.* 149, 1930, 62 pp.

356. Merz, A., and F. Fleischer: Der Einfluss von Nickel auf die Temperaturen der metastabilen und stabilen A_1-Umwandlung eutektischer Eisen-Kohlenstoff und Eisen-Kohlenstoff-Silizium-Legierungen (The Effect of Nickel on the Temperatures of the Metastable and Stable A_1-Transformations of Eutectic Iron-carbon and Iron-carbon-silicon Alloys), *Giesserei*, v. 17, 1930, pp. 817–825.

357. Page, A. R., and J. H. Partridge: The Properties of Some Steels Containing Chromium, *J. Iron Steel Inst.*, v. 121, 1930, pp. 393–415. Also: *Engineering*, v. 129, 1930, pp. 680–683.

358. Pilling, N. B.: Some Effects of Nickel Content in Austenitic Iron-chromium-nickel Alloys, *Proc. Am. Soc. Test. Mat.*, v. 30, part 2, 1930, pp. 278–290.

359. Roberts, O. L., and W. P. Davey: An X-ray Study of the A_3 Point of Iron and Some Iron-nickel Alloys, *Metals & Alloys*, v. 1, 1930, pp. 648–654.

360. Russell, J. H.: Nickel-chromium Alloys, *J. Birmingham Met. Soc.*, v. 10, 1930, pp. 187–209. Also: *Metal Industry*, London, v. 36, 1930, pp. 377–379, 429–432.

361. Sauvageot, M., and L. Lauprète: Attaque de divers types d'aciers inoxydables par les principaux acides usuels (Attack of Various Types of Stainless Steels by the Principal Commonly Used Acids), *Rev. de Mét., Mém.*, v. 27, 1930, pp. 362–367.

362. Sauveur, A.: Steel at Elevated Temperatures, *Trans. Am. Soc. Steel Treat.*, v. 17, 1930, pp. 410–448.

363. Schoenmaker, P.: Zerreiss- und Schlagversuche bei tiefen Temperaturen (Tensile and Impact Tests at Low Temperatures), *First Communications of the New Int. Assoc. Test. Mat.*, Group A, 1930, pp. 237–250.

364. Scott, H.: Expansion Properties of Low-expansion Fe-Co-Ni Alloys, *Trans. Am. Inst. Min. Met. Eng.*, v. 89, 1930, pp. 506–537.

365. Strauss, J.: Report of Committee A-10 on Iron-chromium, Iron-chromium-nickel, and Related Alloys, *Proc. Am. Soc. Test. Mat.*, v. 30, part 1, 1930, pp. 255–258, tables (inserts) V to XV.

366. Vanick, J. S., and P. D. Merica: Corrosion- and Heat-resistant Nickel-copper-chromium Cast Iron, *Trans. Am. Soc. Steel Treat.*, v. 18, 1930, pp. 923–942. Also: *Iron & Steel of Canada*, v. 13, 1930, pp. 241–242, 260–261, 263.

367. Wever, F., and W. Jellinghaus: Zur Kenntnis des Zweistoffsystems Eisen-Vanadin (The Binary System Iron-vanadium), *Mitt. K.-W. Inst. Eisenforschung*, v. 12, 1930, pp. 317–322.

368. WIBERG, O.: High Pressures and Temperatures for Steam Prime
Movers, International Congress General Mechanics, Liége, 1930,
Proc., v. 2, pp. 118–127. Condensed: *Engineering*, v. 133, 1932,
pp. 27–28.

1931

369. ABORN, R. H., and E. C. BAIN: The Wrought Austenitic Alloys, in
"Symposium on Effect of Temperature on the Properties of Metals,"
American Society for Testing Materials and American Society of
Mechanical Engineers, Philadelphia and New York, 1931, pp. 466–
494.
370. ADAMS, L. H., and J. W. GREEN: The Influence of Hydrostatic Pressure
on the Critical Temperature of Magnetisation for Iron and Other
Materials, *Phil. Mag.*, ser. 7, v. 12, 1931, pp. 361–380.
371. ANASTASIADIS, L., and W. GUERTLER: Beispiel eines instabilen Zu-
standes in Legierungen, der sich auch bei 1000° nicht zur Reaktion
bringen lässt (Fe-Ni Legierungen) (An Example of an Unstable
Condition in Alloys Which Even at 1000° Cannot be Changed into
Equilibrium. Fe-Ni Alloys) *Z. f. Metallkunde*, v. 23, 1931, pp.
189–190.
372. ANON.: L'emploi des aciers austénitiques pour les soupapes de moteurs
à explosion (The Use of Austenitic Steels for Internal Combustion
Engine Valves), *Aciers Spéciaux*, v. 6, 1931, pp. 106–108.
373. ANON.: Hochmagnetische Legierungen aus Nickel-Eisen für Mess-
geräte und Messwandler (Highly Magnetic Iron-nickel Alloys for
Measuring Instruments and Instrument Transformers), *Archiv
Tech. Messen*, 1931, Z913-2.
374. BENNEK, H., and P. SCHAFMEISTER: Untersuchungen über das Gebiet
der delta-gamma Umwandlung im System Eisen-Nickel (The Area
of Delta-gamma Transformation of the Iron-nickel System), *Archiv
f. d. Eisenhüttenwesen*, v. 5, 1931–1932, pp. 123–125.
375. BOLTON, J. W., and H. BORNSTEIN: Effect of Elevated Temperatures
on Certain Mechanical Properties of Gray Cast Iron and Malleable
Iron, in "Symposium on Effect of Temperature on the Properties
of Metals," American Society for Testing Materials, and American
Society of Mechanical Engineers, Philadelphia and New York, 1931,
pp. 436–465.
376. BREDIG, G., and E. S. VON BERGKAMPF: Über hexagonales Nickel (On
Hexagonal Nickel), *Z. physik. Chemie*, Bodenstein-Festband, 1931,
pp. 172–176.
377. DIETSCH, G.: Magnetostriktion ferromagnetischer Stoffe (Magneto-
striction of Ferromagnetic Substances), *Z. tech. Physik*, v. 12, 1931,
pp. 380–389.
378. ESAU, A.: Über den Quereffekt der Magnetostriktion (The Transverse
Magnetostrictive Effect), *Physikalische Z.*, v. 32, 1931, pp. 483–485.
379. GREULICH, E.: Die Vergütung eines hochlegierten austenitischen
Chrom-Nickel-Stahls durch Ausscheidungshärtung (Precipitation

Hardening of a High-alloy Austenitic Chromium-nickel Steel), *Archiv f. d. Eisenhüttenwesen*, v. 5, 1931–1932, pp. 323–330.

380. HADFIELD, R. A.: A Research on Faraday's "Steel and Alloys," *Phil. Trans. Royal Soc.*, London, ser. A, v. 230, 1931, pp. 221–292.

381. HALL, J. H.: Fe-Mn-Ni-C, a New Manganese Steel, *Metal Progress*, v. 20, 1931, No. 5, pp. 69–72.

382. HENSEL, F. R.: Age Hardening of Austenite, *Trans. Am. Inst. Min. Met. Eng.*, v. 95, 1931, pp. 255–283.

383. JENKINS, C. H. M., and H. J. TAPSELL: Some Alloys for Use at High Temperatures. Complex Iron-nickel-chromium Alloys.—Part III. The Effect of Composition and Exposure to High Temperatures, *J. Iron Steel Inst.*, v. 123, 1931, pp. 313–343. Also: *Iron Steel Ind.*, v. 4, 1931, pp. 379–380. Also: *Engineering*, v. 131, 1931, pp. 713–716. Also: *Foundry Tr. J.*, v. 45, 1931, pp. 43–44, 48, 120–122.

384. KAHLBAUM, W., R. L. DOWDELL, and W. A. TUCKER: The Tensile Properties of Alloy Steels at Elevated Temperatures as Determined by the "Short Time" Method, *Bur. Stand. J. Research*, v. 6, 1931, pp. 199–218.

385. KAYSER, J. F.: Heat-resisting Alloys, *Foundry Tr. J.*, v. 45, 1931, pp. 412, 414; discussion, v. 46, 1932, p. 180.

386. KERSTEN, M.: Über den Einfluss des elastischen Spannungszustandes auf die Grösse der Anfangspermeabilität (The Effect of Elastic Tension on the Magnitude of Initial Permeability), *Z. tech. Physik*, v. 12, 1931, pp. 665–669.

387. KROLL, W.: Die Legierungen des Berylliums mit Eisen (Iron-beryllium Alloys), *Wiss. Veröffentl. a. d. Siemens-Konzern*, v. 10, 1931, No. 2, pp. 33–34.

388. KÜHLEWEIN, H.: Einige Versuche über die magnetische Nachwirkung (Investigations on Magnetic After-effect), *Physikalische Z.*, v. 32, 1931, pp. 472–480.

389. KÜHLEWEIN, H.: Über die magnetischen Eigenschaften der Perminvare (The Magnetic Properties of Perminvars), *Wiss. Veröffentl. a. d. Siemens-Konzern*, v. 10, 1931, No. 2, pp. 72–88.

390. MASIYAMA, Y.: On the Magnetostriction of Iron-nickel Alloys, *Sci. Rept.*, Sendai, ser. 1, v. 20, 1931, pp. 574–593.

391. MASUMOTO, H.: On the Thermal Expansion of the Alloys of Iron, Nickel, and Cobalt, and the Cause of the Small Expansibility of Alloys of the Invar Type, *Sci. Rept.*, Sendai, ser. 1, v. 20, 1931, pp. 101–123.

392. MEHL, R. F., and C. S. BARRETT: Studies upon the Widmanstätten Structure. I—Introduction. The Al-Ag System and the Cu-Si System, *Trans. Am. Inst. Min. Met. Eng.*, v. 93, 1931, pp. 78–122.

393. NEUMANN, H.: Über ballistische Messungen an hochpermeablen Materialien (Ballistic Measurements on High-permeability Materials), *Wiss. Veröffentl. a. d. Siemens-Konzern*, v. 10, 1931, No. 2, pp. 54–71.

394. PHRAGMÉN, G.: X-ray Investigation of Certain Nickel Steels of Low Thermal Expansion, *J. Iron Steel Inst.*, v. 123, 1931, pp. 465–477.

395. PILLING, N. B., and R. WORTHINGTON: The Effect of Temperature on Some Properties of Iron-chromium-nickel Alloys, in "Symposium on Effect of Temperature on the Properties of Metals," American Society for Testing Materials, and American Society of Mechanical Engineers, Philadelphia and New York, 1931, pp. 495–556.

396. ROMANOV, M. M.: (Rheostat Materials from Ternary Alloys of Iron, Nickel, and Manganese), *Trudy Inst. Metallov*, v. 1, 1931, pp. 195–203. Abst.: *J. Inst. Metals*, v. 50, 1932, p. 227.

397. SANFOURCHE A., and A. PORTEVIN: Attaque de divers alliages par les solutions phosphoriques (Attack of Various Alloys by Phosphoric Acid Solutions), *C. R. Acad. Sci.*, Paris, v. 193, 1931, pp. 53–55.

398. SCOTT, H.: Transformational Characteristics of Iron-manganese Alloys, *Trans. Am. Inst. Min. Met. Eng.*, v. 95, 1931, pp. 284–306.

399. SÖHNCHEN, E., and E. PIWOWARSKY: Über den Einfluss der Legierungselemente Nickel, Silizium, Aluminium und Phosphor auf die Löslichkeit des Kohlenstoffs im flüssigen und festen Eisen (The Effect of the Alloying Elements Nickel, Silicon, Aluminum, and Phosphorus on the Solubility of Carbon in Liquid and in Solid Iron), *Archiv f. d. Eisenhüttenwesen*, v. 5, 1931–1932, pp. 111–121.

400. VOGEL, R., and H. BAUR: Über das ternäre System Eisen-Nickel-Phosphor (The Ternary System Iron-nickel-phosphorus), *Archiv f. d. Eisenhüttenwesen*, v. 5, 1931–1932, pp. 269–278.

401. WASMUHT, R.: Über die Ausscheidungshärtung des Eisens durch Titan (Precipitation Hardening of Iron by Titanium Addition), *Archiv f. d. Eisenhüttenwesen*, v. 5, 1931–1932, pp. 45–56. Also: *Kruppsche Monatshefte*, v. 12, 1931, pp. 159–178.

402. WIDDER, W.: Elastizitätsmodul, Temperatur und Schmelzpunkt (Modulus of Elasticity, Temperature, and Melting Point), *Physikalische Z.*, v. 32, 1931, pp. 349–351.

403. YENSEN, T. D.: Permeability of Hipernik Reaches 167,000, *Electric J.*, v. 28, 1931, pp. 386–388.

1932

404. AUSTIN, C. R., and G. P. HALLIWELL: Some Developments in High-temperature Alloys in the Nickel-cobalt-iron System, *Trans. Am. Inst. Min. Met. Eng.*, v. 99, 1932, pp. 78–100.

405. BAIN, E. C.: On the Rates of Reactions in Solid Steel, *Trans. Am. Inst. Min. Met. Eng.*, v. 100, 1932, pp. 13–46.

406. BISCHOFF, K.: Untersuchungen über die Änderung einiger Eigenschaften (α-γ Umwandlung, Härte, elektrische Leitfähigkeit, magnetische Eigenschaften) von Eisen-Chrom-Nickel und Eisen-Chrom-Molybdän Legierungen durch Wärmebehandlung (Effect of Heat Treatment on Some Properties—Alpha-gamma Transformation, Hardness, Electric Conductivity, Magnetic Properties—of Iron-chromium-nickel and of Iron-chromium-molybdenum Alloys), *Mitt. Forsch.-Inst. Vereinigte Stahlwerke A.-G., Dortmund*, v. 3, 1932–1933, pp. 249–266.

407. CHEVENARD, P.: Propriétés électriques des alliages de fer et de nickel dans un large intervale de température (Electric Properties of Iron-

nickel Alloys over a Great Temperature Interval), *Revue du Nickel*, v. 3, 1932, pp. 55–64.

408. CIOFFI, P. P.: Hydrogenized Iron, *Physical Review*, ser. 2, v. 39, 1932, pp. 363–367. Also: *Bell Lab. Record*, v. 10, 1932, pp. 159–163.

409. DAHL, O.: Zur Frage unterkühlbarer Zustandsänderungen in Eisen-Nickellegierungen. Die hohe Permeabilität von luftgekühltem Permalloy (Supercooling and Transformations of Iron-nickel Alloys. High Permeability of Air-cooled Permalloy), *Z. f. Metallkunde*, v. 24, 1932, pp. 107–111. Extr.: *Z. angew. Chemie*, Aug. 8, 1931, p. 672.

410. ENGLERT, E.: Ferromagnetismus und elektrische Eigenschaften.—VI. Mitteilung. Longitudinale und transversale ferromagnetische Widerstandsänderung (Ferromagnetism and Electric Properties. —VI. Change of Electric Resistivity in Longitudinal and Transverse Magnetic Fields), *Ann. d. Physik*, ser. 5, v. 14, 1932, pp. 589–612.

411. EPSTEIN, S.: Embrittlement of Hot-galvanized Structural Steel, *Proc. Am. Soc. Test. Mat.*, v. 32, part 2, 1932, pp. 293–379.

412. EVERHART, J. L.: Metals That Resist Alkali Corrosion, *Chem. Met. Eng.*, v. 39, 1932, p. 88.

413. FRIEND, J. N.: The Relative Corrodibilities of Ferrous and Non-ferrous Metals and Alloys.—Part III. Final Report. The Results of Three Years' Exposure at Southampton Docks, *J. Inst. Metals*, v. 48, 1932, pp. 109–120.

414. GOLDSCHMIDT, R.: Nachwirkungsverluste in ferromagnetischen Materialien bei schwachen Wechselfeldern (Residual Loss in Ferromagnetic Materials in Weak Alternating Fields), *Z. tech. Physik*, v. 13, 1932, pp. 534–539.

415. GREGG, J. L.: "The Alloys of Iron and Molybdenum," McGraw-Hill Book Company, Inc., New York, 1932, 507 pp.

416. JAEGER, F. M., and E. ROSENBOHM: La détermination exacte des chaleurs spécifiques vraies du tungstène, du rhodium, du palladium, du ruthenium, de l'osmium et de l'iridium à des températures entre 0° and 1625° (The Precise Determination of True Specific Heats of Tungsten, Rhodium, Palladium, Ruthenium, Osmium, and Iridium at Temperatures between 0 and 1625°C.), *Rec. Trav. Chim. Pays-Bas*, v. 51, 1932, pp. 1–46.

417. KAHLBAUM, W., and L. JORDAN: Tensile Properties of Cast Nickel-chromium-iron Alloys and of Some Alloy Steels at Elevated Temperatures, *Bur. Stand. J. Research*, v. 9, 1932, pp. 327–332.

418. KAYSER, J. F.: Heat-resisting Metals and Their Use in the Ceramic Industry, *Foundry Tr. J.*, v. 47, 1932, pp. 263–265, 280–281.

419. KROLL, W.: Legierungen des Galliums (Gallium Alloys), *Metallwirtschaft*, v. 11, 1932, pp. 435–437.

420. KÜHLEWEIN, H.: Über die magnetischen Eigenschaften von Eisen, Nickel, Kobalt und einigen Legierungen bei höheren Temperaturen (The Magnetic Properties of Iron, Nickel, Cobalt, and Some Alloys at Elevated Temperatures), *Wiss. Veröffentl. a. d. Siemens-Konzern*, v. 11, 1932, No. 1, pp. 124–140.

421. LICHTENBERGER, F.: Untersuchung der Magnetostriktion und der Magnetisierung von Einkristallen der Eisen-Nickelreihe (Magneto-

striction and Magnetization of Single-crystal Iron-nickel Alloys), *Ann. d. Physik*, ser. 5, v. 15, 1932, pp. 45–71.

422. LUCKEMEYER-HASSE, L., and H. SCHENCK: Löslichkeit von Wasserstoff in einigen Metallen und Legierungen (Solubility of Hydrogen in Some Metals and Alloys), *Archiv f. d. Eisenhüttenwesen*, v. 6, 1932–1933, pp. 209–214.

423. MILLER, J. L.: An Investigation of Certain Corrosion-resistant Steels.— Part I. Some Alloys for Use in Contact with Sulphuric Acid, *Iron Steel Inst., Carnegie Scholarsh. Mem.*, v. 21, 1932, pp. 111–127.

424. MISHIMA, T.: (Nickel-aluminum Steel for Permanent Magnets), *Ohm*, July 1932 (in Japanese). Abst.: *Stahl u. Eisen*, v. 53, 1933, p. 79.

425. NORBURY, A. L., and E. MORGAN: Nickel-chromium-silicon Cast Irons, *J. Iron Steel Inst.*, v. 126, 1932, pp. 301–321. Abst.: *Metallurgia*, v. 6, 1932, pp. 153–154.

426. PORTEVIN, A., E. PRÉTET, and H. JOLIVET: Durcissement structural à chaud des alliages fer-nickel-tungstène (Structural Hardening at Elevated Temperatures of Iron-nickel-tungsten Alloys), *C. R. Acad. Sci.*, Paris, v. 194, 1932, pp. 1237–1239. Also: *Revue du Nickel*, v. 4, 1933, July, pp. 78–79.

427. PREISACH, F.: Permeabilität und Hysterese bei Magnetisierung in der energetischen Vorzugsrichtung (Permeability and Hysteresis in the Direction of Easiest Magnetization), *Physikalische Z.*, v. 33, 1932, pp. 913–923.

428. REED, E. L.: Influence of Special Elements on the Carbon Content of the Iron-carbon Eutectoid, *Trans. Am. Soc. Steel Treat.*, v. 20, 1932, pp. 115–176.

429. RICKARD, T. A.: "Man and Metals," McGraw-Hill Book Company, Inc., New York, 1932, 2 vol.

430. ROHN, W.: Influence of Gases on Metals and Influence of Melting in Vacuo, Am. Inst. Min. Met. Eng., *Tech. Pub.* 470, 1932, 8 pp.

431. SANDS, J. W.: Invar, Elinvar, and Related Iron-nickel Alloys.—Part II, *Metals & Alloys*, v. 3, 1932, pp. 159–165.

432. SCHEIL, E.: Über die Ursache der Umwandlung des Austenits in Martensit in der Nähe der Raumtemperatur (The Cause of Transformation of Austenite into Martensite near Room Temperature), *Z. f. Elektrochemie*, v. 38, 1932, pp. 554–557. Also: *Z. anorg. allgem. Chemie*, v. 207, 1932, pp. 21–40.

433. SCHMIDT, M., and O. JUNGWIRTH: Warmsprödigkeit austenitischer Stähle (Blue Brittleness of Austenitic Steels), *Archiv f. d. Eisenhüttenwesen*, v. 6, 1932–1933, pp. 559–562.

434. SHUBROOKS, G. E.: Elinvar Hairsprings for Watches, *Metal Progress*, v. 21, 1932, No. 2, pp. 58–63.

435. STÄBLEIN, F.: Technische Werkstoffe grosser magnetischer Weichheit (Technical Materials of Great Magnetic Softness), *Z. tech. Physik*, v. 13, 1932, pp. 532–534.

436. STRAUSS, J.: Castings of Corrosion-resistant Steels, *Proc. Am. Soc. Test. Mat.*, v. 32, part 2, 1932, pp. 213–237.

437. WINKLER, K., and R. VOGEL: Das Zustandsschaubild Eisen-Nickel-Wolfram (The Iron-nickel-tungsten Diagram), *Archiv f. d. Eisenhüttenwesen*, v. 6, 1932–1933, pp. 165–172.

438. YENSEN, T. D.: Hipernik and Other Magnetic Alloys. Great Improvements Due to Heat Treatments, *Metal Progress*, v. 21, 1932, No. 6, pp. 28–34, 70.

1933

439. AIZAWA, T., and G. WACHI: Effect of Tension on Magnetic Property of Permalloy, *Res. Electrotech. Lab.*, Tokyo, No. 351, 1933, 20 pp. (in Japanese).

440. AUWERS, O. VON: Über Volumenmagnetostriktion an Poly- und Einkristallen (Volume Magnetostriction in Poly- and Monocrystals), *Physikalische Z.*, v. 34, 1933, pp. 824–827.

441. BORNHOFFEN, O., and E. PIWOWARSKY: Einfluss von Nickel und Silizium auf das Wachsen von Gusseisen (Effect of Nickel and Silicon on the Growth of Cast Iron), *Archiv f. d. Eisenhüttenwesen*, v. 7, 1933–1934, pp. 269–274.

442. BOSCH, C.: Über die Entwicklung der chemischen Hochdrucktechnik bei dem Aufbau der neuen Ammoniakindustrie (The Chemical High-pressure Technique in the Development of the New Ammonia Industry), *Z. Ver. deutsch. Ing.*, v. 77, 1933, pp. 305–317.

443. BRONIEWSKI, W., and J. SMOLINSKI: Sur la structure des alliages fernickel (The Structure of Iron-nickel Alloys), *C. R. Acad. Sci.*, Paris, v. 196, 1933, pp. 1793–1796.

444. DAHL, O., and J. PFAFFENBERGER: Beitrag zur Kenntnis der Eisen-Nickellegierungen (Contribution to the Knowledge of Iron-nickel Alloys), *Z. f. Metallkunde*, v. 25, 1933, pp. 241–245.

445. DAHL, O., J. PFAFFENBERGER, and H. SPRUNG: Neuartige magnetische Werkstoffe für Pupinspulen (New Magnetic Materials for Pupin Coils), *Elektrische Nachrichten-Technik*, v. 10, 1933, pp. 317–332.

446. FRY, A.: Erhöhung des Korrosionswiderstandes durch Legieren (Increasing Corrosion Resistance by Alloying), *Tech. Mitt. Krupp*, v. 1, 1933, pp. 1–11.

447. GAYLER, M. L. V.: The Constitution of the Alloys of Iron and Manganese, *J. Iron Steel Inst.*, v. 128, 1933, pp. 293–353.

448. GREINER, E. S., J. S. MARSH, and B. STOUGHTON: "The Alloys of Iron and Silicon," McGraw-Hill Book Company, Inc., New York, 1933, 457 pp.

449. HAGEMANN, H., and H. HIEMENZ: Über den Einfluss der Banddicke, der Glühatmosphäre und mitgeglühter Zwischenisolation auf die Anfangs- und Maximal-Permeabilität von gewickelten Bandkernen aus Nickel-Eisen-Legierungen (The Effect of Thickness of Strip, of Annealing Atmosphere, and of Separating Material during Annealing on Initial and Maximum Permeabilities of Coiled Cores of Iron-nickel Alloys), in "Heraeus Vacuumschmelze," Verlag G. M. Albertis, Hanau, 1933, 434 pp. (180–200).

450. HEINDLHOFER, K., and B. M. LARSEN: Rates of Scale Formation on Iron and a Few of Its Alloys, *Trans. Am. Soc. Steel Treat.*, v. 21, 1933, pp. 865–895.

451. HOUDREMONT, E., and H. SCHRADER: Zur Frage der Anlasssprödigkeit (Temper Brittleness), *Archiv f. d. Eisenhüttenwesen*, v. 7, 1933–1934, pp. 49–59.

452. JACOBSON, B., and A. WESTGREN: Über das Nickelcarbid und seine Beziehung zu den übrigen Carbiden der Elementreihe Scandium-Nickel (Nickel Carbide and Its Relation to the Other Carbides of the Element Series Scandium-nickel), *Z. physik. Chemie*, ser. B, v. 20, 1933, pp. 361–367.

453. JONES, B.: Investigations into the Nitrogen Hardening of Steels.— Part II. The Nitriding Properties of Some Chromium and Austenitic Steels at a Temperature of 500°C., *Iron Steel Inst., Carnegie Scholarsh. Mem.*, v. 22, 1933, pp. 51–96.

454. KERSTEN, M.: Über den Temperaturkoeffizienten des Elastizitäts-moduls ferromagnetischer Stoffe. Zur Deutung des Elinvar (The Temperature Coefficient of the Modulus of Elasticity of Ferro-magnetic Substances. A Contribution to the Interpretation of Elinvar), *Z. f. Physik*, v. 85, 1933, pp. 708–716.

455. KEULEGAN, G. H., and M. R. HOUSEMAN: Temperature Coefficient of the Moduli of Metals and Alloys Used as Elastic Elements, *Bur. Stand. J. Research*, v. 10, 1933, pp. 289–320.

456. KÖSTER, W.: Dauermagnetwerkstoffe auf der Grundlage der Aus-scheidungshärtung (Permanent Magnets on the Basis of Precipita-tion Hardening), *Stahl u. Eisen*, v. 53, 1933, pp. 849–856.

457. KÖSTER, W.: Das System Eisen-Nickel-Aluminium (The Iron-nickel-aluminum System), *Archiv f. d. Eisenhüttenwesen*, v. 7, 1933–1934, pp. 257–262.

458. KUSSMANN, A., B. SCHARNOW, and W. STEINHAUS: Über das Permalloy Problem (The Permalloy Problem), in "Heraeus Vacuumschmelze," Verlag G. M. Albertis, Hanau, 1933, pp. 310–338.

459. MCKIBBEN, W. E.: The Coreless Induction Furnace as a Laboratory Tool, *Trans. Am. Foundrymen's Assoc.*, v. 41, 1933, pp. 66–81.

460. MAURER, E., and H. KORSCHAN: Beitrag zur Kenntnis der mechani-schen Eigenschaften grösster Schmiedestücke (Mechanical Properties of Very Large Forgings), *Stahl u. Eisen*, v. 53, 1933, pp. 209–215, 243–251, 271–281.

461. PFAFFENBERGER, J.: Ermittlung der magnetischen Eigenschaften an kleinen Blechproben (Determination of Magnetic Properties on Small Sheet Specimens), *Archiv f. d. Eisenhüttenwesen*, v. 7, 1933–1934, pp. 117–120.

462. PFEIL, L. B., and D. G. JONES: A Contribution to the Study of the Properties of Austenitic Steels, *J. Iron Steel Inst.*, v. 127, 1933, pp. 337–389.

463. POGODIN, S. A., A. I. BASS, G. A. KAHAN, E. M. LEKARENKO, and V. I. MICHEEV: Proizvodstvo nichroma (The Manufacture of Nichrome), *Metallurg*, v. 8, 1933, No. 3, pp. 19–35.

464. RANDALL, W. F.: A Useful Instrument Alloy. The Characteristics and Applications of Mumetal, *Electrical Review*, v. 112, 1933, p. 42.

465. ROLL, F.: Beiträge zum Einfluss des Ni und Si auf die Mischungslücke des Fe-Cu Systems im festen Zustand (Contributions to the Effect of Nickel and Silicon on the Solubility Gap of the Iron-copper System in the Solid State), *Z. anorg. allgem. Chemie*, v. 212, 1933, pp. 61–64.

466. SCHULZE, A.: Die Magnetostriktion.—III (Magnetostriction.—III), *Z. f. Physik*, v. 82, 1933, pp. 674–683.

467. SHELTON, S. M., and W. H. SWANGER: Thermal Conductivity of Irons and Steels and Some Other Metals in the Temperature Range 0 to 600°C., *Trans. Am. Soc. Steel Treat.*, v. 21, 1933, pp. 1061–1078.

468. STANBERY, L. J.: Heat-resisting Chromium-nickel-iron Alloys for Furnace Construction, *Metals & Alloys*, v. 4, 1933, pp. 127–135, 159–164.

469. STEINBERGER, R. L.: Magnetic Properties of Iron-nickel Alloys under Hydrostatic Pressure, *Physics*, v. 4, 1933, pp. 153–161.

470. SYKES, W. P.: The Cobalt-tungsten System, *Trans. Am. Soc. Steel Treat.*, v. 21, 1933, pp. 385–423.

471. TAMMANN, G., and V. CAGLIOTI: Die Erholung des elektrischen Widerstandes und der Härte binärer Eisenmischkristalle von den Folgen der Kaltbearbeitung (The Recovery of Electric Resistivity and of Hardness of Binary Iron Solid Solutions from Cold Working), *Ann. d. Physik*, ser. 5, v. 16, 1933, pp. 680–684.

472. TAMMANN, G., and H. J. ROCHA: Über die Änderung der magnetischen Induktion bei konstanter Feldstärke durch Kaltbearbeitung und die Erholung beim Erhitzen (Change of Magnetic Induction at Constant Field Strength by Cold Working and Recovery upon Heating), *Ann. d. Physik*, ser. 5, v. 16, 1933, pp. 861–864.

473. TUCKER, W. A., and S. E. SINCLAIR: Creep and Structural Stability of Nickel-chromium-iron Alloys at 1600°F., *Bur. Stand. J. Research*, v. 10, 1933, pp. 851–862.

474. ZACHARIAS, J.: The Temperature Dependence of Young's Modulus for Nickel, *Physical Review*, ser. 2, v. 44, 1933, pp. 116–122.

1934

475. AHRENS, E.: Über die Temperaturabhängigkeit der wahren spezifischen Wärme des Nickels (The Effect of Temperature on the True Specific Heat of Nickel), *Ann. d. Physik*, ser. 5, v. 21, 1934, pp. 169–181.

476. BOZORTH, R. M.: Theory of the Heat Treatment of Magnetic Materials, *Physical Review*, ser. 2, v. 46, 1934, pp. 232–233.

477. BRAGG, W. L., and E. J. WILLIAMS: The Effect of Thermal Agitation on Atomic Arrangement in Alloys, *Proc. Royal Soc.*, London, ser. A, v. 145, 1934, pp. 699–730.

478. CHEVENARD, P.: Étude thermomagnétique de l'hétérogénéité d'une austénite fer-nickel-carbone-chrome consécutive à la précipitation de carbure, par l'effet du revenu (Thermo-magnetic Study of the Heterogeneity of an Austenitic Iron-nickel-carbon-chromium Alloy

after Carbide Precipitation by Means of the Effect of Tempering), *C. R. Acad. Sci.*, Paris, v. 198, 1934, pp. 1144–1146.

479. DAHL, O., and J. PFAFFENBERGER: Magnetisches Sonderverhalten kaltgewalzter Eisen-Nickel-Legierungen durch Ausscheidungshärtung (Special Magnetic Behavior of Cold-rolled Iron-nickel Alloys owing to Precipitation Hardening), *Metallwirtschaft*, v. 13, 1934, pp. 527–530, 543–549, 559–563.

480. DAHL, O., and J. PFAFFENBERGER: Hysteresearme und stabile Werkstoffe für die Fernmeldetechnik (Low-hysteresis Materials of Great Magnetic Stability Used in Telephony), *Z. tech. Physik*, v. 15, 1934, pp. 99–106.

481. DEHLINGER, U.: Kinetik und Zustandschaubild der irreversiblen Umwandlung im System Eisen-Nickel (Kinetics and Phase Diagram of the Irreversible Transformation in the Iron-nickel System), *Z. f. Metallkunde*, v. 26, 1934, pp. 112–116.

482. ELLIS, W. C., and E. E. SCHUMACHER: Magnetic Materials—A Survey in Relation to Structure, *Metals & Alloys*, v. 5, 1934, pp. 269–276; v. 6, 1935, pp. 26–29.

483. FRENCH, H. J., and J. W. SANDS (editors): "Nickel Alloy Steels," The International Nickel Co., Inc., New York, 1934, 7 sections.

484. FRIEND, J. N.: The Final Examination of the Second Series of Iron and Steel Specimens, Exposed at Colombo for 10 Years, in "Fourteenth (Interim) Report of the Committee of the Institution of Civil Engineers," H. M. Stationery Office, London, 1934, pp. 27–40.

485. GLOCKER, R., H. PFISTER, and P. WIEST: Röntgenuntersuchungen an α-Eisenmagnetlegierungen (X-ray Examination of Alpha-phase Magnet Steels), *Archiv f. d. Eisenhüttenwesen*, v. 8, 1934–1935, pp. 561–563.

486. GREGG, J. L.: "The Alloys of Iron and Tungsten," McGraw-Hill Book Company Inc., New York, 1934, 511 pp.

487. GREGG, J. L., and B. N. DANILOFF: "The Alloys of Iron and Copper," McGraw-Hill Book Company, Inc., New York, 1934, 454 pp.

488. GREW, K. E.: The Specific Heat of Nickel and of Some Nickel-copper Alloys, *Proc. Royal Soc.*, London, ser. A, v. 145, 1934, pp. 509–522.

489. HESSENBRUCH, W., and W. ROHN: Ein kernloser Induktionsofen für Drehstrom von Netzfrequenz (A Coreless Induction Furnace for Alternating Current of Standard Power-line Frequency), *Stahl u. Eisen*, v. 54, 1934, pp. 77–82.

490. HONDA, K., H. MASUMOTO, and Y. SHIRAKAWA: On New K. S. Permanent Magnet, *Sci. Rept.*, Sendai, ser. 1, v. 23, 1934, pp. 365–373.

491. JONES, B.: Investigations into the Nitrogen Hardening of Steels.— Part IV. The Nitriding of High-chromium and Austenitic Steels at Various Temperatures, *Iron Steel Inst., Carnegie Scholarsh. Mem.*, v. 23, 1934, pp. 179–204.

492. KELSALL, G. A.: Permeability Changes in Ferromagnetic Materials Heat Treated in Magnetic Fields, *Physics*, v. 5, 1934, pp. 169–172.

493. KELSALL, G. A., and H. J. WILLIAMS: Apparatus for Making Permeability-tension Tests, *Rev. Sci. Instruments*, v. 5, 1934, pp. 437–440.

494. KERSTEN, M.: Über anomale Eigenschaften neuer magnetischer Werkstoffe (Anomalous Properties of New Magnetic Materials), *Wiss. Veröffentl. a. d. Siemens-Konzern*, v. 13, 1934, No. 3, pp. 1–9.

495. KERSTEN, M.: Physikalische Untersuchungen an neuen magnetischen Werkstoffen (Physical Investigation of New Magnetic Materials), *Z. tech. Physik*, v. 15, 1934, pp. 249–257.

496. KÖSTER, W.: Das System Eisen-Nickel-Molybdän (The Iron-nickel-molybdenum System), *Archiv f. d. Eisenhüttenwesen*, v. 8, 1934–1935, pp. 169–171.

497. KÖSTER, W., and W. SCHMIDT: Zusammenhang zwischen Gitterparameter und Ferromagnetismus (Connection between Lattice Parameter and Ferromagnetism), *Archiv f. d. Eisenhüttenwesen*, v. 8, 1934–1935, pp. 25–27.

498. KÖSTER, W., and W. TONN: Zusammenhang zwischen dem Gefügeaufbau der Eisenlegierungen und ihrem Verschleiss bei der Prüfung nach M. Spindel (Connection between the Constitution of Iron Alloys and Their Wear as Determined on the Spindel Machine), *Archiv f. d. Eisenhüttenwesen*, v. 8, 1934–1935, pp. 111–115.

499. KÜHLEWEIN, H.: Über die Eigenschaften der ferromagnetischen Legierungen des ternären Systems Eisen-Nickel-Vanadin (The Properties of the Ferromagnetic Alloys of the Ternary Iron-nickel-vanadium System), *Z. anorg. allgem. Chemie*, v. 218, 1934, pp. 65–88.

500. McKEEHAN, L. W.: Ferromagnetism in Metallic Crystals, *Trans. Am. Inst. Min. Met. Eng.*, v. 111, 1934, pp. 11–52.

501. MESSKIN, W. S., and E. SOMIN: Eigenschaften von Nickel-Aluminium Magnetstahl (Properties of Nickel-aluminum Magnet Steel), *Archiv f. d. Eisenhüttenwesen*, v. 8, 1934–1935, pp. 315–318. Abst.: *Metallurgist*, June 28, 1935, pp. 39–41.

502. MÜLLER-BERGHAUS, J.: Anwendung von Stahlrekuperatoren auf Eisenhüttenwerken (The Use of Steel Recuperators in Steel Mills), *Stahl u. Eisen*, v. 54, 1934, pp. 822–827.

503. MUSATTI, I., and A. REGGIORI: Ricerche sugli acciai per valvole di motori a scoppio e sulle loro caratteristiche alle temperature elevate (Investigation of Combustion-engine Valve Steels and of Their High-temperature Characteristics), *Metallurgia Italiana*, v. 26, 1934, pp. 457–498, 569–599, 675–689, 765–793. Extract: *Rev. de Mét., Mém.*, v. 31, 1934, pp. 420–438.

504. NEUMANN, H.: Neue magnetische Legierung "1040" mit hoher Anfangspermeabilität (The New Magnetic Alloy "1040" with High Initial Permeability), *Archiv Tech. Messen*, 1934, Z913-5.

505. NEUMANN, H.: Über magnetische Kreise, deren Permeabilität im Bereiche ihres Maximums konstant ist (Magnetic Circuits of Constant Maximum Permeability), *Wiss. Veröffentl. a. d. Siemens-Konzern*, v. 13, 1934, No. 3, pp. 10–30.

506. PREISACH, F.: Magnetische Untersuchungen an ausscheidungsfähigen Eisen-Nickel-Legierungen (Magnetic Investigations of Precipitation-hardening Iron-nickel Alloys), *Z. f. Physik*, v. 93, 1934–1935, pp. 245–268.

507. SCHEIL, E., and W. TONN: Vergleich von Brinell- und Ritzhärte (Comparison of Brinell and Scratch Hardness), *Archiv f. d. Eisenhüttenwesen*, v. 8, 1934–1935, pp. 259–262.

508. SCHULZE, A.: Über elektrische Widerstandsmaterialien (Electric-resistance Materials), *Metallwirtschaft*, v. 13, 1934, pp. 369–372.

509. SIX, W., J. L. SNOEK, and W. G. BURGERS: Een nieuw magnetisch materiaal voor de kernen van pupinspoelen (A New Magnetic Material for the Cores of Pupin Coils), *De Ingenieur*, v. 49, 1934, pp. E195–E200.

510. WILLIAMS, C.: Thermal Expansion and the Ferromagnetic Change in Volume of Nickel, *Physical Review*, ser. 2, v. 46, 1934, pp. 1011–1014.

511. ZAIMOVSKY, A. S., J. E. NARODITZKY, and D. J. LOUBOVITCH: Zelezo-Nikel-Aluminievie Splavi dla postoyannych magnitov c visikoi koercitivnoi siloi (Iron-nickel-aluminum Alloys for Permanent Magnets of High Coercive Force), *Vestnik Metallopromishlennosti*, v. 14, 1934, No. 8–9, pp. 140–153.

1935

512. AUSTIN, J. B.: Dependence of Rate of Transformation of Austenite on Temperature, *Trans. Am. Inst. Min. Met. Eng.*, v. 116, 1935, pp. 309–317.

513. AUWERS, O. VON, and H. NEUMANN: Über Eisen-Nickel-Kupfer-Legierungen hoher Anfangspermeabilität (Iron-nickel-copper Alloys of High Initial Permeability), *Wiss. Veröffentl. a. d. Siemens-Werken*, v. 14, 1935, No. 2, pp. 93–108.

514. BOZORTH, R. M.: Present Status of Ferromagnetic Theory, *Elec. Engineering*, v. 54, 1935, pp. 1251–1261.

515. BOZORTH, R. M., and J. F. DILLINGER: Heat Treatment of Magnetic Materials in a Magnetic Field.—II. Experiments with Two Alloys, *Physics*, v. 6, 1935, pp. 285–291.

516. BURGERS, W. G., and J. L. SNOEK: Lattice Distortion and Coercive Force in Single Crystals of Nickel-iron-aluminum, *Physica*, v. 2, 1935, pp. 1064–1074.

517. BURGERS, W. G., and J. L. SNOEK: Über die Walz- und Rekristallisationstextur des Nickeleisens (Structures of Rolled and of Recrystallized Iron-nickel Alloys), *Z. f. Metallkunde*, v. 27, 1935, pp. 158–160.

518. CHAMBEYRON, J.: Forgeage et estampage des aciers inoxydables (Forging and Stamping of Corrosion-resistant Steels), *Métaux*, v. 10, 1935, pp. 291–293.

519. CHEVENARD, P., and X. WACHÉ: Effet accélérateur d'une tension mécanique sinusoïdale sur le revenu d'une austénite fer-nickel-chrome-carbone hypertrempée (Accelerated Tempering of Hyperquenched Iron-nickel-chromium-carbon Austenitic Alloys by Mechanical Stressing), *C. R. Acad. Sci.*, Paris, v. 201, 1935, pp. 261–263.

520. CLEAVES, H. E., and J. G. THOMPSON: "The Metal—Iron," McGraw-Hill Book Company, Inc., New York, 1935, 574 pp.

521. CLUSIUS, K., and J. GOLDMANN: Zur Atomwärme des Nickels bei tiefen Temperaturen (The Atomic Heat of Nickel at Low Temperatures), *Z. physik. Chemie*, ser. *B*, v. 31, 1935–1936, pp. 256–262.

522. CRAWFORD, C. H., and E. J. THOMAS: Silicon Steel in Communication Equipment, *Elec. Engineering*, v. 54, 1935, pp. 1348–1353.

523. DAHL, O., and F. PAWLEK: Einfluss von Faserstruktur und Magnetfeldabkühlung auf den Magnetisierungsverlauf (Effect of Fiber Structure and of Cooling in a Magnetic Field on Magnetization), *Z. f. Physik*, v. 94, 1935, pp. 504–522.

524. DAHL, O., F. PAWLEK, and J. PFAFFENBERGER: Die magnetischen Eigenschaften elektrolytisch erzeugter Eisenbleche (The Magnetic Properties of Iron Sheets Produced Electrolytically), *Archiv f. d. Eisenhüttenwesen*, v. 9, 1935–1936, pp. 103–112.

525. DAHL, O., J. PFAFFENBERGER, and N. SCHWARTZ: Zur Kenntnis der Eisen-Nickel-Legierungen (Iron-nickel Alloys), *Metallwirtschaft*, v. 14, 1935, pp. 665–670.

526. DILLINGER, J. F., and R. M. BOZORTH: Heat Treatment of Magnetic Materials in a Magnetic Field.—I. Survey of Iron-cobalt-nickel Alloys, *Physics*, v. 6, 1935, pp. 279–284.

527. ELMEN, G. W.: Magnetic Alloys of Iron, Nickel, and Cobalt, *Elec. Engineering*, v. 54, 1935, pp. 1292–1299. Also: *Bell System Tech. J.*, v. 15, 1936, pp. 113–135.

528. EVANS, U. R.: Theoretical Aspects of Oxidation, in "Review of Oxidation and Scaling of Heated Solid Metals," Dept. Sci. Ind. Research, H. M. Stationery Office, London, 1935, pp. 1–17.

529. GEIGER, G. F : Higher Chromium-nickel Irons, in "The Book of Stainless Steels," American Society for Metals, Cleveland, 2d ed., 1935, pp 461–475.

530. HUNTER, M. A.: Electrical Resistors, in "The Book of Stainless Steels," American Society for Metals, Cleveland, 2d ed., 1935, pp. 426–434.

531. KORNETZKI, M.: Der Magnetostriktionsvolumeneffekt von Nickel und Magnetit (The Volume Magnetostrictive Effect of Nickel and of Magnetite), *Z. f. Physik*, v. 97, 1935, pp. 662–666.

532. KORNETZKI, M.: Über die Abhängigkeit der Volumenmagnetostriktion und des Weissschen Faktors von der Temperatur und der Gitterkonstante (The Dependence of Volume Magnetostriction and of the Weiss Factor on Temperature and Lattice Constant), *Z. f. Physik*, v. 98, 1935–1936, pp. 289–313.

533. KÖSTER, W., and W. DANNÖHL: Das System Kupfer-Nickel-Eisen (The Copper-nickel-iron System), *Z. f. Metallkunde*, v. 27, 1935, pp. 220–226.

534. MARSH, J. S.: "The Principles of Phase Diagrams" McGraw-Hill Book Company, Inc., New York, 1935, 193 pp.

535. NAKAMURA, K.: The Effect of Magnetization on Young's Modulus of Elasticity of Some Ferromagnetic Substances, *Sci. Rept.*, Sendai, ser. 1, v. 24, 1935, pp. 303–331.

536. NEUMANN, H : Über magnetisch harte Eisen-Nickel-Kupfer-Legierungen (Magnetically Hard Iron-nickel-copper Alloys), *Metallwirtschaft*, v. 14, 1935, pp. 778–779.

537. PAWLEK, F.: Walz- und Rekristallisationstexturen bei Eisen-Nickel-
    legierungen im Zusammenhang mit den magnetischen Eigenschaften
    (Structures of Rolled and of Recrystallized Iron-nickel Alloys and
    Their Relation to Magnetic Properties), *Z. f. Metallkunde*, v. 27,
    1935, pp. 160–165.

538. PÖLZGUTER, F.: Die neuere Entwicklung der Werkstoffe für Dauer-
    magnete (Recent Development in Steels for Permanent Magnets),
    Stahl u. Eisen, v. 55, 1935, pp. 853–860.

539. POPOV, R. V.: Proizvodstvo nichroma (The Manufacture of Nichrome),
    Vestnik Metallopromishlennosti, v. 15, 1935, No. 1, pp. 87–103.

540. SCHEIL, E.: Die Irreversibilität der Eisen-Nickel-Legierungen und
    ihr Gleichgewichtsschaubild (Irreversibility of Iron-nickel Alloys
    and Their Equilibrium Diagram), *Archiv f. d. Eisenhüttenwesen*, v.
    9, 1935–1936, pp. 163–166.

541. SCHEIL, E., and K. KIWIT: Einfluss von Legierungszusätzen auf das
    Zundern des Eisens (The Effect of Alloying Additions on the Scaling
    of Iron), *Archiv f. d. Eisenhüttenwesen*, v. 9, 1935–1936, pp. 405–416.
    Also (K. Kiwit only): *Mitt. d. Kohle- u. Eisenforschung*, v. 1, No. 2,
    July, 1935, pp. 9–28.

542. SEYBOLT, A. U., and C. H. MATHEWSON: Solubility of Oxygen in Solid
    Cobalt and the Upper Transformation Point of the Metal, *Trans.
    Am. Inst. Min. Met. Eng.*, v. 117, 1935, pp. 156–172.

543. SNOEK, J. L.: Magnetische Untersuchungen an Pupinkernen neuer
    Bauart (Magnetic Investigation of Pupin Coils of Modern Construc-
    tion), *Physica*, v. 2, 1935, pp. 403–412.

544. SPELLER, F. N.: "Corrosion—Causes and Prevention," McGraw-Hill
    Book Company, Inc., New York, 2d ed., 1935, 694 pp.

545. STEPANOW, D., F. MARSCHAK, N. BALASCHOWA, and W. KABANOWA:
    Die Auflösung der elektrolytischen Niederschläge von Fe-Ni-
    Legierungen (Corrosion of Electrolytic Deposits of Fe-Ni Alloys),
    Z. f. Elektrochemie, v. 41, 1935, pp. 597–599.

546. THUM, E. E. (editor): "The Book of Stainless Steels," American
    Society for Metals, Cleveland, 2d ed., 1935, 787 pp.

547. WALTERS, F. M., JR., and C. WELLS: The Constitution of the Binary
    Alloys of Iron and Manganese, *Trans. Am. Soc. Metals*, v. 23, 1935,
    pp. 727–750.

548. WEIS, A.: Ferromagnetische Stoffe für Hochfrequenz (Ferromagnetic
    Materials for High Frequency), *Archiv Tech. Messen*, 1935, Z911-5.

549. WHITE, A. E., and C. L. CLARK: Creep at High Temperatures, in "The
    Book of Stainless Steels," American Society for Metals, Cleveland,
    2d ed., 1935, pp. 557–568.

550. WOOD, T. J.: Thermal Expansion Characteristics of Some Nickel Cast
    Irons, *Trans. Am. Soc. Metals*, v. 23, 1935, pp. 455–468.

1936

551. American Society for Metals: "Metals Handbook," The Society,
    Cleveland, 1936, pp. 378–380.

552. AUWERS, O. von: "Gmelins Handbuch der anorganischen Chemie. Eisen.—Teil D. Magnetische und elektrische Eigenschaften der legierten Werkstoffe" (Gmelin's Handbook of Inorganic Chemistry. Iron.—Part D. Magnetic and Electric Properties of Alloys), Verlag Chemie, G. m. b. H., Berlin, 8th ed., 1936, 466 pp.

553. BALLAY, M.: Constitution et durcissement structural d'austénites au glucinium carburées (Constitution and Structural Hardening of Austenitic Beryllium Alloys Containing Carbon), *C. R. Acad. Sci.,* Paris, v. 203, 1936, pp. 724–726.

554. BOZORTH, R. M.: Determination of Ferromagnetic Anisotropy in Single Crystals and in Polycrystalline Sheets, *Physical Review,* ser. 2, v. 50, 1936, pp. 1076–1081.

555. CONE, E. F.: Carbon and Low-alloy Steels, in "Symposium on High-strength Constructional Metals," Pittsburgh Regional Meeting, American Society for Testing Materials, March 4, 1936, pp. 1–30 (29–30).

556. DAHL, O.: Kaltverformung und Erholung bei Legierungen mit geordneter Atomverteilung (Cold Deformation and Recovery of Alloys with Ordered Atomic Distribution), *Z. f. Metallkunde,* v. 28, 1936, pp. 133–138.

557. DAHL, O., and F. PAWLEK: Walz- und Rekristallisationstexturen bei Eisen-Nickel-Legierungen im Zusammenhang mit den magnetischen Eigenschaften.—II (Structures of Rolled and of Recrystallized Iron-nickel Alloys and Their Relation to Magnetic Properties.—II), *Z. f. Metallkunde,* v. 28, 1936, pp. 230–233.

558. DEHLINGER, U.: Die Volumänderung bei der Magnetisierung und die Invarlegierungen (Volume Changes upon Magnetization and Invar Alloys), *Z. f. Metallkunde,* v. 28, 1936, pp. 194–196.

559. DÖRING, W.: Über die Temperaturabhängigkeit der Magnetostriktion von Nickel (Effect of Temperature on Magnetostriction of Nickel), *Z. f. Physik,* v. 103, 1936, pp. 560–582.

560. EPSTEIN, S.: "The Alloys of Iron and Carbon," Vol. I—Constitution, McGraw-Hill Book Company, Inc., New York, 1936, 476 pp.

561. EWART, M.: Exact Measurements of Specific Heats at High Temperatures.—XXV. Specific Heats and Allotropism of Nickel between 0° and 1000°C., *Koninkl. Akad. van Wetenschappen (Proc. Royal Acad. Sci.),* Amsterdam, v. 39, 1936, pp. 833–838.

562. DGF (FINK, D. G.): The New Permanent-magnet Alloys, *Electronics,* v. 9, 1936, May, pp. 30–32, 35.

563. HANSEN, M.: "Der Aufbau der Zweistofflegierungen" (Constitution of Binary Alloys), Julius Springer, Berlin, 1936, 1100 pp.

564. HUNTER, M. A.: Alloys of Iron and Nickel with Low Expansion Coefficients, in "Metals Handbook," American Society for Metals, Cleveland, 1936, pp. 345–349.

565. JELLINGHAUS, W.: Neue Legierungen mit hoher Koerzitivkraft (New Alloys with High Coercive Force), *Z. tech. Physik,* v. 17, 1936, pp. 33–36.

566. JETTE, E., and F. FOOTE: X-ray Study of Iron-nickel Alloys, *Trans. Am. Inst. Min. Met. Eng.*, v. 120, 1936, pp. 259–276.

567. KIRCHNER, H.: Über den Einfluss von Zug, Druck und Torsion auf die Längsmagnetostriktion (The Effect of Tension, Compression, and Torsion on Longitudinal Magnetostriction), *Ann. d. Physik*, ser. 5, v. 27, 1936, pp. 49–69.

568. KLEIS, J. D.: Ferromagnetic Anisotropy of Nickel-iron Crystals at Various Temperatures, *Physical Review*, ser. 2, v. 50, 1936, pp. 1178–1181.

569. LEGG, V. E.: Magnetic Measurements at Low Flux Densities Using the Alternating Current Bridge, *Bell System Tech. J.*, v. 16, 1936, pp. 39–62.

570. McKAY, R. J., and R. WORTHINGTON: "Corrosion Resistance of Metals and Alloys," Reinhold Publishing Corporation, New York, 1936, 492 pp.

571. MACMILLAN, C.: A New Analysis of *B-H* Curves and Its Application to Ferromagnetic Behavior, *General Electric Rev.*, v. 39, 1936, pp. 225–231, 284–292.

572. MERICA, P. D.: Constitution of Iron-nickel Alloys, in "Metals Handbook," American Society for Metals, Cleveland, 1936, pp. 271–273.

573. MESSKIN, W. S., and J. M. MARGOLIN: Über die magnetische Stabilität von ferromagnetischen Eisen-Legierungen (The Magnetic Stability of Ferromagnetic Iron Alloys), *Z. f. Physik*, v. 101, 1936, pp. 456–477.

574. MOSER, H.: Messung der wahren spezifischen Wärme von Silber, Nickel, β-Messing, Quarzkristall und Quarzglas zwischen +50 und 700°C. nach einer verfeinerten Methode (An Improved Method for Measuring the True Specific Heat of Silver, Nickel, β-brass, Crystalline and Fused Silica between 50 and 700°C.), *Physikalische Z.*, v. 37, 1936, pp. 737–753.

575. NISHINA, T.: An Investigation on Some Magnetic Alloys, *Sci. Rept.*, Sendai, ser. 1, v. 25A, 1936, pp. 344–361.

576. OWEN, E. A. and E. L. YATES: X-ray Measurements of the Thermal Expansion of Pure Nickel, *Phil. Mag.*, ser. 7, v. 21, 1936, pp. 809–818.

577. PORTEVIN, A., E. PRÉTET, and J. DELACOMBE: Contribution à l'étude de la forgeabilité. Recherche d'un essai de laboratoire (Contribution to the Study of Forgeability. Investigation of a Laboratory Test), *Rev. de Mét., Mém.*, v. 33, 1936, pp. 114–132. Also: International Congress, Min. Met., Paris, 1935, v. 2, (Met.), pp. 339–357.

578. POWELL, R. W.: The Thermal and Electrical Conductivities of Metals and Alloys.—Part II. Some Heat-resisting Alloys from 0°C. to 800°C., *Proc. Phys. Soc.*, London, v. 48, 1936, pp. 381–392.

579. SCHULZE, A.: Über eine besondere Erscheinung bei Umwandlungen, die sich über ein Temperaturgebiet erstrecken (A Special Phenomenon Observed in Transformations Which Occur over a Temperature Interval), *Physikalische Z.*, v. 37, 1936, pp. 41–43.

580. SIEGEL, S., and S. ROSIN: The Variation of Young's Modulus with Magnetization in Permalloy, *Physical Review*, ser. 2, v. 49, 1936, p. 863.

581. SNOEK, J. L.: On the "Permalloy Problem," *Nature*, v. 137, 1936, p. 493.

582. STONER, E. C.: The Specific Heat of Nickel, *Phil. Mag.*, ser. 7, v. 22, 1936, pp. 81–106.

583. WASSERMANN, G.: Untersuchungen an Eisen-Nickel-Legierungen mit Würfeltextur (Investigations on Iron-nickel Alloys with Cubic Texture), *Z. f. Metallkunde*, v. 28, 1936, pp. 262–265.

584. WICKENDEN, T. H.: Nickel as an Alloying Element in Steel, in "Metals Handbook," American Society for Metals, Cleveland, 1936, pp. 411–416.

585. WOLDMAN, N. E., and A. J. DORNBLATT: "Engineering Alloys," American Society for Metals, Cleveland, 1936, 622 pp.

1937

586. ALEXANDER, W. O., and N. B. VAUGHAN: The Constitution of the Nickel-aluminium System, *J. Inst. Metals*, v. 61, 1937, pp. 247–263.

587. BOZORTH, R. M.: Directional Ferromagnetic Properties of Metals, *J. Applied Physics*, v. 8, 1937, pp. 575–588.

588. BRADLEY, A. J., A. H. JAY, and A. TAYLOR: The Lattice Spacing of Iron-nickel Alloys, *Phil. Mag.*, ser. 7, v. 23, 1937, pp. 545–557.

589. BRADLEY, A. J., and A. TAYLOR: An X-ray Investigation of the Cause of High Coercivity in Iron-nickel-aluminum Alloys, *Nature*, v. 140, 1937, pp. 1012–1013.

590. CHEVENARD, P., L. HUGUENIN, X. WACHÉ, and A. VILLACHON: Nouveaux alliages, du type élinvar susceptibles de durcissement structural (New Elinvar-type Alloys Responding to Structural Hardening), *Génie Civil*, v. 110, 1937, p. 470. Also: *C. R. Acad. Sci.*, Paris, v. 204, 1937, pp. 1231–1233.

591. CHEVENARD, P., and X. WACHÉ: Corrosion intercristalline des ferronickels chromés carburés, écrouis après hypertrempe (Intercrystalline Corrosion of Iron-nickel-chromium-carbon Alloys Cold Drawn after Quenching), *Génie Civil*, v. 110, 1937, pp. 444–445. Also: *C. R. Acad. Sci.*, Paris, v. 199, 1934, pp. 861–863; v. 204, 1937, pp. 1167–1169.

592. DERGE, G., and A. R. KOMMEL: Structures of Meteoric Irons, *Am. J. Sci.*, v. 34, 1937, pp. 203–214.

593. EBERT, H., and A. KUSSMANN: Änderung der Sättigungsmagnetisierung durch allseitigen Druck (Change of Saturation Magnetization owing to Omnilateral Compression), *Physikalische Z.*, v. 38, 1937, pp. 437–445.

594. ELLWOOD, W. B., and V. E. LEGG: Study of Magnetic Losses at Low Flux Densities in 35 Permalloy Sheet, *J. Applied Physics*, v. 8, 1937, pp. 351–358.

595. EVANS, U. R.: "Metallic Corrosion, Passivity and Protection," Edward Arnold & Company, London, 1937, 720 pp.

596. GAYLER, M. L. V., and C. WAINWRIGHT: Alloys of Iron Research.—Part XII. Note on the β_M Transformation in Manganese-rich Iron-manganese Alloys, *J. Iron Steel Inst.*, v. 135, 1937, pp. 267–280.

597. GOLDSCHMIDT, R.: Über magnetische Stabilität (Magnetic Stability), *Helv. Phys. Acta*, v. 10, 1937, pp. 225–236.

598. HAWORTH, F. E.: Energy of Lattice Distortion in Cold-worked Permalloy, *Physical Review*, ser. 2, v. 52, 1937, pp. 613–620.

599. HESSENBRUCH, W.: Beitrag zur Kenntnis der Legierung Kovar (Contribution to the Knowledge of Kovar), *Z. f. Metallkunde*, v. 29, 1937, pp. 193–195.

600. LEGAT, H.: Magnetisch harte, C-arme Nickel-Kupfer-Stähle (Magnetically Hard Low-carbon Nickel-copper Steels), *Metallwirtschaft*, v. 16, 1937, pp. 743–749.

601. McKEEHAN, L. W.: Ferromagnetic Anisotropy in Nickel-cobalt-iron Crystals at Various Temperatures, *Physical Review*, ser. 2, v. 51, 1937, pp. 136–139.

602. NEUMANN, H.: Werkstoffe für Dauermagnete (Permanent-magnet Materials), *Archiv Tech. Messen*, 1937, Z912-1.

603. NEUMANN, H., A. BÜCHNER, and H. REINBOTH: Mechanisch weiche Dauermagnetlegierungen aus Kupfer, Nickel und Eisen (Mechanically Soft Iron-nickel-copper Permanent-magnet Alloys), *Z. f. Metallkunde*, v. 29, 1937, pp. 173–185.

604. OWEN, E. A., and E. L. YATES: X-ray Investigation of Pure Iron-nickel Alloys.—Part 1. Thermal Expansion of Alloys Rich in Nickel, *Proc. Phys. Soc.*, v. 49, 1937, pp. 17–28.

605. OWEN, E. A., and E. L. YATES: X-ray Investigation of Pure Iron-nickel Alloys.—Part 2. Thermal Expansion of Some Further Alloys, *Proc. Phys. Soc.*, v. 49, 1937, pp. 178–188.

606. OWEN, E. A., E. L. YATES, and A. H. SULLY: An X-ray Investigation of Pure Iron-nickel Alloys.—Part 4. The Variation of Lattice Parameter with Composition, *Proc. Phys. Soc.*, v. 49, 1937, pp. 315–322.

607. OWEN, E. A., E. L. YATES, and A. H. SULLY: An X-ray Investigation of Pure Iron-nickel Alloys.—Part 5. The Variation of Thermal Expansion with Composition, *Proc. Phys. Soc.*, v. 49, 1937, pp. 323–325.

608. POMP, A., and G. WEDDIGE: Warmwalzversuche an Kohlenstoff- und hochlegierten Stählen bei verschiedenen Walzbedingungen (The Effect of Different Rolling Practice on the Hot Rolling of Carbon and High-alloy Steels), *Mitt. K.-W. Inst. Eisenforschung*, v. 19, 1937, pp. 65–86.

609. RANDALL, W. F.: Nickel-iron Alloys of High Permeability, with Special Reference to Mumetal, *J. Inst. Elec. Eng.*, v. 80, 1937, pp. 647–658.

610. SCHMIDT, M., and L. WETTERNIK: Über die Säurebeständigkeit von Legierungen auf der Grundlage Eisen-Nickel (The Corrosion Resistance of Iron-nickel Base Alloys), *Korrosion u. Metallschutz*, v. 13, 1937, pp. 184–189.

611. SEYFFERT, E.: Über die Nachwirkungsverluste von Nickel-Eisen-Legierungen (Residual Losses of Nickel-iron Alloys), *Z. tech. Physik*, v. 18, 1937, pp. 200–203.

612. Sisco, F. T.: "The Alloys of Iron and Carbon," Vol. II—Properties, McGraw-Hill Book Company, Inc., New York, 1937, 777 pp.

613. Stäblein, F.: Eisenlegierungen mit besonderen magnetischen Eigenschaften (Iron Alloys with Special Magnetic Properties), in "Werkstoff-Handbuch Stahl u. Eisen," Stahleisen Verlag m. b. H., Düsseldorf, 2d ed., 1937, O–41, pp. 1–8.

614. Steinhaus, W., A. Kussmann, and E. Schoen: Sättigungsmagnetisierung und Annäherungsgesetz des Eisens (Saturation Magnetization and the Law of Approach of Iron), *Physikalische Z.*, v. 38, 1937, pp. 777–785.

615. Van Vleck, J. H.: On the Anisotropy of Cubic Ferromagnetic Crystals, *Physical Review*, ser. 2, v. 52, 1937, pp. 1178–1198.

616. Weddige, G.: Warmwalzversuche an unlegierten und hochlegierten Stählen bei verschiedenen Walzbedingungen (The Effect of Different Rolling Practice on the Hot Rolling of Carbon and High-alloy Steels), *Stahl u. Eisen*, v. 57, 1937, pp. 913–921.

1938

617. Engler, O.: Der Elastizitätsmodul ferromagnetischer Stoffe in Abhängigkeit von der Temperatur und vom Magnetfeld (Effects of Temperature and of Magnetic Field on the Modulus of Elasticity of Ferromagnetic Materials), *Ann. d. Physik*, ser. 5, v. 31, 1938, pp. 145–163.

618. Mott, N. F.: Magnetism and the Electron Theory of Metals, in "Physics in Industry—Magnetism," The Institute of Physics, London, 1938, pp. 1–15.

619. Wells, C.: Graphitization in High-purity Iron-carbon Alloys, *Trans. Am. Soc. Steel Treat.*, v. 26, 1938, pp. 289–357.

NAME INDEX

(Item numbers in the Bibliography are in **boldface**; numbers of the pages
where the reference is quoted follow the boldface numerals.)

B

SUBJECT INDEX

B

Barrett effect (*see* Magnetostriction, volume)
Bulk modulus (*see* Modulus of bulk)

Calcium, desulphurizer, 10
Coefficient of thermal expansion (*see* Thermal expansion)
Coercive force, iron-nickel alloys, 220–225
    effect of cold work, 222, 223
    effect of composition, 221, 222
    effect of cooling in magnetic field, 224, 225
    effect of heat treatment, 222
    effect of mechanical and thermal treatment, 223–225
    effect of pressure, 224
    effect of tension, 224
  iron-nickel-aluminum alloys, 263, 296–299
    effect of heat treatment, 298
  iron-nickel-beryllium alloys, 266, 267
  iron-nickel-cobalt alloys, 287
  iron-nickel-cobalt-aluminum alloys, 300
  iron-nickel-cobalt-molybdenum alloys, 290
  iron-nickel-cobalt-titanium alloys, 301, 302
  iron-nickel-copper alloys, 302–307
    effect of cold work, 305, 306
  iron-nickel-copper-molybdenum alloys, 252
  iron-nickel-silver alloys, 268
  iron-nickel-vanadium alloys, 263
Cohenite, 6
Cold working, iron-nickel alloys, 18–21
  iron-nickel-chromium alloys, 18–21
  iron-nickel-copper alloys, 20
Compressibility, iron-nickel alloys, 109–111
Compressive strength, iron-nickel alloys, 380, 381
Conpernik, 244
Copernik, 244
Core loss, iron-nickel alloys, at high inductions, 229–231
    at low inductions, 233–238
  iron-nickel-copper-molybdenum alloys, 252
  low inductions, theory, 233–235
    (*See also* Eddy-current loss; Hysteresis loss; Residual loss)

577

O

R

S